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# *The* AMERICAN PHYSICS TEACHER

VOLUME 4 FEBRUARY, 1936 NUMBER 1


## Albert Abraham Michelson: the Man and the Man of Science


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ALBERT ABRAHAM MICHELSON was a world figure. Seldom does a man of science so capture the imagination of all classes of people that he is unfailing front-page copy for the daily press, and yet maintain such a quality of scientific work for more than half a century that his results in the most profoundly fundamental fields of study remain unquestioned as to fact. Seldom has a man so supreme in his own technical work achieved a personality so simple and unaffected that in the dazzling blaze of publicity his step has never faltered. Michelson never set great store by his opinions, never for a moment mistook them for facts. He never published a sentence that could serve as an origin for controversy.

Such a personality can be felt, but how can it be described or analyzed? Who for example can hope adequately to describe and analyze the sea? Despite all our knowledge of the sea, a recital of its scientific characteristics gives as inadequate a picture of the sea as a similar recital of positions, titles, and honors gives of the individual on whom they have been bestowed.

The sea and Michelson had much in common. "Illimitable" and "unfathomable" and "serene" are adjectives that have been applied to both ere now,[1] and the parallelism goes much further. Michelson's life was a magnificient exhibition of singleness of purpose unruffled by the winds of favor or disfavor. Even those cosmic human forces of love, hate, jealousy, envy, and ambition seemed to move him little. He possessed an astonishing indifference to people in general, yet he had devoted friends, and when occasions arose where these friends or associates needed his support no one was ever more quick than he to champion their causes. In such situations his clarity of vision, fearlessness, and swift assumption of initiative usually won the desired result with little effective opposition.

The secrets of the depths of the sea are still her own. Of Michelson also one knew the surface, little more; one sensed much that could not be fathomed. Very few people ever knew him intimately.

There is often perhaps a sense of mystery that surrounds the primitive. His simplicity was an aspect of the primitive. His intuition towards nature, the boldness and the brilliance of his attack upon those citadels wherein she kept her most carefully treasured secrets, the extremely fundamental character of his inquiries, were primitive. Accordingly, one is tempted to trace the parallel between that primitive vitality of Michelson and that same primitive vital quality of the sea that made her the mother of all life. Such attributes are not blazoned forth; they are exhaled softly, gently, and are sensed by subtle processes that we possess at times but do not understand. Again, in the matchless play of color, light and shade of the sea and sky, and in the cadences of sound, ranging from the treble patter of rain on quiet water to the thundering basso of the surf, are further suggestions of this personality that included art and music as well as

[1] F. R. Moulton, Pop. Astron. 39, 308 (1931).

science, not in separate compartments, but as different aspects of an individual and a completely integrated whole.

Michelson was born at Strelno, Germany, a small Prussian town near the frontier of Poland, on December 19, 1852. Brought by his parents at the age of two to San Francisco his interest in science became evident to his teacher in a high school in that city and he was urged to continue his education. He felt the call of the sea, however, and took the competitive examination for Congressional appointment to the U. S. Naval Academy. The result was a tie between himself and another boy. The latter being the son of a Civil War veteran, who was also a local politician, naturally got the appointment. The story of what followed—taken rather freely from an address by Professor H. G. Gale, to whom Michelson once related it—illustrates his tenacity of purpose. Urged by the Examining Committee to try for one of the ten appointments at large this youth of seventeen set out for Washington to interview President Grant. He was armed with letters from his high school teachers, from the Congressman, and from the father of his rival.

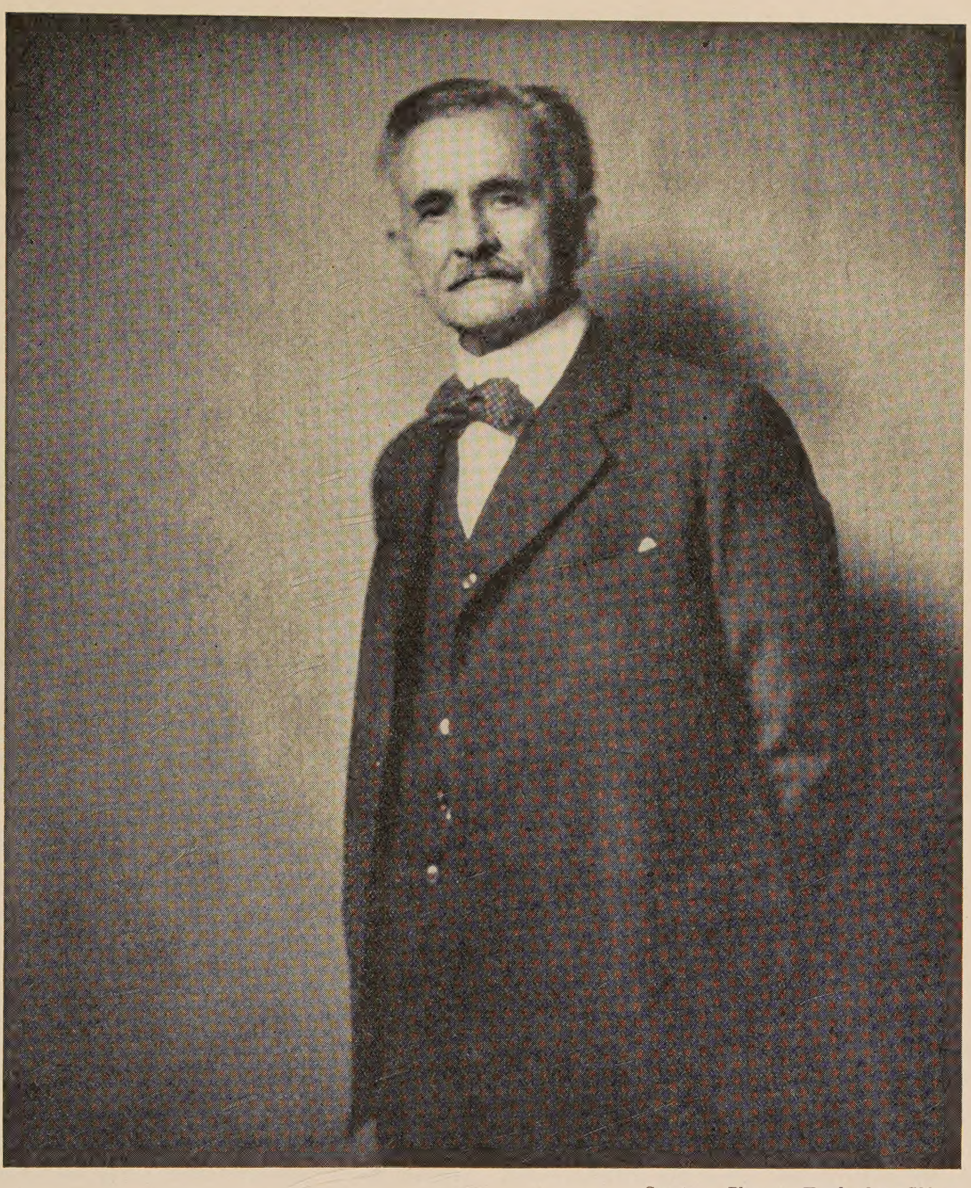
The doorkeeper at the White House asked for the letters, but the young man refused to give them to anyone but the President himself. He obtained his interview. President Grant said that he had exhausted his ten appointments at large, and while they were talking it over, one of the high officials of the Navy came in for a conference. Michelson was undoubtedly a very handsome boy at that age. Those of us who remember his coal black hair, his sparkling eyes, realize that this must have been the case. The Admiral turned to the President and asked who he was. The President explained that the young man had come on from San Francisco, hoping to get an appointment to the Naval Academy. The Admiral said, "You come over to Annapolis with me. One of the boys failed in the examination. He explained that he was ill on the day of the examination. We are giving him a second chance, and if he fails there will be a vacancy."

Michelson went to Annapolis, and waited for three days. Finally they told him that the boy who was ill had taken his second examination, had passed satisfactorily. The Admiral said, "I am afraid there is nothing we can do." Michelson went down to the train, put his trunk aboard and prepared to go back to Washington to see President Grant again. When the train was starting a midshipman went through calling for him. He said, "The Commandant wants to see you." Between them they stopped the train, removed the trunk from the baggage car and went to the Commandant's office. Here he was told, "The President has appointed you as one of the appointees at large." Professor Michelson used to add, when he related this story, "It was the eleventh appointment and entirely illegal."

Michelson's entire scientific career, begun while a student at Annapolis and continued without pause until, in his seventy-ninth year, he suffered a cerebral hemorrhage that caused his death, is summed up for posterity in some 78 published papers. The first,[2] consisting of one page, was printed in 1878 when he was 26 years of age and is entitled "On a Method of Measuring the Velocity of Light." The last, containing an introduction written by himself ten days before he lost consciousness, and but recently published, is on the same subject.

Light in some aspect or other was the topic of all but ten of these papers. Michelson's life work in this field lay chiefly along two avenues. The first was the accurate determination of the speed of light. In this field, neither the young man of 26 nor the old man of 79 has ever had a rival. It is remarkable testimony to the world-wide confidence in his ability, honesty and judgment, that during his life no one ever attempted to repeat his experiments or check his results on this subject excepting himself. Michelson's first interest in this problem was aroused when he was a student under Simon Newcomb, professor of physics at the Naval Academy. The latter had been carrying on an elaborate investigation supported by thousands of dollars of Congressional appropriations, and could well have been forgiven for incredulity and some irritation when his work was matched in accuracy by this stripling with an outfit built by himself and costing ten dollars. Newcomb writes under date of February 20, 1880, in an introduction to Michelson's paper officially required by Naval etiquette, "To pre-

[2] See the numbered bibliography at the end of the present article.



*Courtesy, Florence Hendershot, Chicago*

Albert Abraham Michelson

vent a possible confusion of this determination of the velocity of light with another now in progress under official auspices, it may be stated that the credit and responsibility for the present paper rests with Master Michelson." Again in the preface to the official paper it is stated "that the degree of precision originally aimed at can be reached without any radical change in the instrument." The invitation was extended to cooperate with any other physicist who desired to use it (the official instrument) for further researches.

Michelson, however, had made a radical modification in the instrument. He shifted the rotating mirror from its classical position where it had been placed by Foucault, the first to use it, in 1862, and where it was used by Newcomb, to a different location in the optical path. This shift enabled the light to be sent a far greater distance and back without excessive enfeeblement. It was

this brilliant idea that made it possible for his crude apparatus to compete with the official one, and that subsequently enabled Michelson, when he had greater resources at his command, to extend the path for many miles and so obtain precision undreamed of, and impossible by any other device that has been invented. Michelson's own last determination shows an accuracy of 3 parts in $10^6$; that is to say, the 186,000-odd mile journey made by light in one second is known to within half a mile.

Michelson entered on the second great avenue he was destined to pursue, the study of interference of light, also very early in life. At the age of 30 he published his sixth paper, an article of nine pages entitled "The Relative Motion of the Earth and the Luminiferous Ether." In this field he was destined to have many follow his lead, but still only two competitors ever came near to equalling his precision and none even remotely showed his wealth of originality and resourcefulness. This highway of discovery on which he entered was as fundamental as the other but, unlike it, led into regions which certainly even Michelson could never have foreseen.

One branch went into the microcosmos, the world of atoms hopelessly removed from direct human vision, and furnished us with as direct evidence as any that we have of the kinetic dance of molecules that we call temperature. His thirtieth paper, entitled "On the Broadening of Spectral Lines," gives little less than a direct demonstration of equipartition of energy in the thermal motion of atoms of no less than 17 different elements ranging in atomic weight from 1 to 210.

Another branch of his work on interference, *interferometry* as it has come to be called, led out into the macrocosmos of the stars. When the lay world 15 years ago read in scare heads on the front pages of the press, "Michelson Measures Size of Betelgeuse" the scientific world was somewhat amused that a method 30 years old had suddenly become a "news story." In 1890 his 20th paper (21 pages, one of the longest he ever wrote), dealt with observations on a double star (Capella), too close for resolution by the best telescopes of the time. In the following year his 21st paper was on the "Measurements of Jupiter's Satellites by Interference"; this work was done at Lick Observatory. Thirty years elapsed before the astronomers reverted to his technic to measure the giant star Betelgeuse.

However, these majestic flights to outer space and then to inner space were but digressions, perhaps we might better say momentary pauses, which never long diverted him from the end he had in view when starting on this avenue of study. This end was to discover, if possible, the absolute motion of the earth, as, trailing along with the rest of the solar family, it followed the sun's plunging course through space. The wave character of light had been established, by other experiments as well as his own on interference; and, in common with all other wave phenomena that are known, light was thought to require a medium for its propagation. This medium, the ether, was believed to be universal in extent, and to afford a fixed frame in space to which all motions might be referred. Indeed, had it not been for the experiments which Michelson was about to undertake, we should probably today be living in a scientific world dominated by the same idea.

Shortly after leaving the Naval Academy and going to Case School of Applied Science at Cleveland, Michelson had repeated his experiment on the speed of light with better apparatus. He had also measured the speed of light in water and in carbon disulphide, and found the values in these mediums to be in a complete agreement with classical theory which related the speed to the refractive index of the medium. What more natural, therefore, than that he should in addition send his beam of light up-stream and back through the free ether of space and, by comparing the time required for this journey with that required for a similar beam to travel transversely across the current, thus determine the rate of flight of the earth through this fixed and all-pervading medium?

This experiment required an almost unbelievable delicacy of observation, and for the purpose he invented and built with funds provided by Alexander Graham Bell a device by means of which the light waves themselves were made to measure that excessively minute retardation that they would suffer in going up-stream and back instead of across the current. This device was his refractometer, later called the *interferometer*. The theory of it was published in his eighth paper in

1882. It was not surprising that the first instrument built should have been found not to possess sufficient rigidity of structure. He gave it thorough trials at Berlin and at Potsdam. But the very manipulation of it produced considerably greater alterations in the light paths than those expected from its motion through the ether and this first result was negative. Consequently, during the next five years, in collaboration with Professor Morley, an apparatus was constructed of such stability that it was capable of measuring about 1/12 part of the displacement of the interference fringes expected as a result of the earth's motion through the ether. To the complete astonishment and mystification of the scientific world this refined experiment also yielded absolutely negative results. Again must we note at this point the universal confidence with which any experimental fact announced by Michelson was instantly accepted. Not for twenty years did anyone have the temerity to challenge his conclusion. Instead, the theoretical physicists accepted it and in one way or another began to rebuild their theories. Many of the proposals seemed bizarre at the time, and most of them were satisfactory only to their own authors.

It was not until 1905 when Albert Einstein, taking Michelson's experimental result as one fundamental postulate and the constancy of the speed of light as the other, brought out his paper on "The Special Theory of Relativity" that the world in general accepted his interpretation of these results as a cornerstone of its physical philosophies. While Michelson himself professed that subsequent developments of the general theory of relativity were beyond his understanding, he undoubtedly was of the opinion that Einstein's interpretation of his experiment was a correct one. Nevertheless, he took great pains to leave no stone unturned to test any alternative hypothesis which could be put to experimental test either before or after the appearance of the relativity theory. For example, when in 1897 it was proposed in explanation of his negative result that possibly the ether at the surface of the earth was dragged along with a speed so nearly equal to that of the earth that within the limits of accuracy of the experiment no change in motion could be detected, Michelson sent his two interfering pencils of light around a vertical rectangle of 50 by 200 ft., making the entire vertical circuit of Ryerson Laboratory. Over so long a path irregularities in the air would completely destroy the requisite sensitivity, and consequently here for the first time he sent the beam in a vacuum. To this practice he later frequently made recourse, as in his last experiment on light's speed. This vertical interferometer showed a displacement of less than 1/20 of a fringe which indicated that *if* the ether *were* dragged by the earth, this drag would extend out in space presumably to a distance of several thousand miles, a conclusion that common sense rejected as highly improbable.

Again, at the request of certain of the relativists, especially Silberstein in 1925, he spent many thousands of dollars building an apparatus along lines which he had himself proposed in his 45th paper in 1904 and at that time rejected as showing positive evidence only of the earth's rotation in the ether but not of its translatory motion. The writer well remembers the reluctance with which Michelson engaged upon this expensive enterprise. He did it obviously only out of deference to the desires of some of these advocates of the theory of relativity, whose mathematical arguments he modestly professed he was unable to refute. At the breaking-up of a luncheon meeting during which his assent to the project had been obtained, he remarked in conclusion, "Well gentlemen, we will undertake this, although my conviction is strong that we shall prove only that the earth rotates on its axis, a conclusion which I think we may be said to be sure of already." The result, published in collaboration with H. G. Gale as his 74th paper in 1925, turned out precisely as he had prophesied. In this experiment both classical theory and the theory of relativity predicted the same results, a shift of 236/1000 of the distance between fringes. The experiment, performed on the prairies west of Chicago near the little town of Clearing, showed a displacement of 230/1000, in very close agreement with the prediction. The rotation of the earth received another independent proof, the theory of relativity another verification. But neither fact had much significance. This is a clear example of Michelson's remarkable intuition and insight with respect to physical phenomena. One of his younger associates in the laboratory has written in this connection, "Michelson saw with

intuition unsurpassed the logical relationship between phenomena, where others were forced to spend months in mathematical calculations to reach the desired results. His judgment in scientific matters was supreme."

A recent chapter of this puzzling question of ether drift was published in 1928 under the title, "A Conference on the Michelson and Morley Experiment." Michelson's part in this was his 77th contribution and the last of which he ever read the proof sheets. The conference was held at Pasadena in that year and resulted from the fact that long before, Professor D. C. Miller, who had been associated with Morley at Cleveland after Michelson left to go to Clark University, had carried on at different times extending over a great number of years, subsequent experiments on ether drift, first with Morley and then by himself. The tremendous importance of the problem fully justified Miller's long continued attack, in which by the patient acquisition of one hundred thousand individual observations he hoped to achieve a precision correspondingly greater than Michelson's dozen odd of earlier years. The announcement in the scientific journals by Miller that a very minute residual of drift had been detected and that its orientation in space was approximately in the direction of flight of the solar system, revived world-wide interest in the problem.

To this conference at Pasadena came Lorentz who with Fitzgerald had years before proposed a theory of a contraction of the instrument in the direction of motion, just sufficient to compensate the effect of ether drift. This Fitzgerald-Lorentz contraction had been the most widely accepted explanation of the negative result prior to the work of Einstein. Experimenters came likewise to this conference; notably Kennedy, who had designed an apparatus of great precision for repeating these experiments independently, and who had won expressions of enthusiastic admiration from Michelson for the beauty of his device. Piccard's results too were discussed; Piccard on one of his balloon ascensions had carried an interferometer 7000 ft. aloft and also had set one up on top of the Rigi. The result of all of these experiments, excepting Miller's, were absolutely negative, and the discussion as to the interpretation of Miller's experiments wound up in a state of utter confusion, as discussions so often do.

Other aspects of Michelson's activity which lay along this highway of research on interference should be mentioned. One of his earliest ideas was that of calibrating our standards of length in terms of the changeless wave-lengths emitted by atomic systems. In 1887 he published in collaboration with Professor Morley a paper of three pages entitled, "On a Method of Making the Wave-Length of Sodium Light the Actual and Practical Standard of Length." His "Plea for Light Waves," an address in the following year before the physics section of the American Association for the Advancement of Science, expressed the same idea. This work came to its fruition six years later when, by invitation of the International Committee on Weights and Measures, Michelson set up an interferometer in Paris and found that the standard meter contained 1,553,163.5 waves of the red radiation of cadmium.

In his search for a sufficiently simple and homogeneous radiation to serve for so precise a purpose, Michelson had laid the foundations in the whole field of spectroscopic measurements, of those technics that for a time enabled spectroscopists to boast that their work involved the most accurate measurements of the smallest quantities in the whole field of science. That light waves can be measured to a precision of about 1 part in $10^7$ is due very largely to those trails blazed by Michelson as he digressed now and then from the main aim of his work on interference.

Explicitly and implicitly we have already referred to Michelson's willingness to cooperate with his colleagues. This was true of him even when these colleagues were specialists in altogether different fields. The most interesting example of his cooperative work is illustrated in his experiments on the determination of the rigidity of the earth. In the first decade of this century geologists had begun to realize the significance of an idea originally proposed by Kelvin in 1863, that our earth, in spite of an interior temperature admittedly high enough to reduce almost any substance to the liquid state, nevertheless gives evidence from its dynamics as it spins around the sun of being approximately as rigid as steel. Experiments to verify this apparent paradox by

measuring directly the earth's rigidity, by such notable men as C. C. and Horace Darwin, Schweydar, Heckel, and others, had given inconclusive results. These workers invariably had used delicate pendulum apparatus. The late Thomas Crowder Chamberlin, professor of geology at the University of Chicago, one of that distinguished group of men who with Michelson were brought together for the founding of a great university in the middle west, engaged the latter in conversation one noon at luncheon upon this subject. He asked him if he could think of any way in which the problem might be attacked on the basis of a physical experiment. With characteristic reserve, Michelson replied that he would be glad to think about it and with characteristic dispatch a few days later informed his friend that he had a very simple method in mind by means of which he thought the desired result might be achieved.

In none of Michelson's investigations, perhaps, did his simplicity and directness of attack show itself more clearly. The apparatus, a complete departure from what had been used formerly, was not only highly original, but simplicity itself. It consisted primarily of two 6-in. iron pipes 500 ft. long, buried in the ground and half filled with water. At either end of the pipes were pits where observations could be made. To avoid the tumult of a great city, the experiment was conducted on the campus of the Yerkes Observatory at Lake Geneva. The earth's rigidity was measured by the tiny tides in these two artificial, sheltered, miniature seas. The sea again had given him inspiration. Observations made at first with simple microscopes proved too laborious, and the interferometer was again called into service. For such a problem, however, the interferometer would be far too sensitive. It had to be adulterated very generously to bring its record conveniently within the range of automatic recording by motion picture cameras. Even then, it happened once or twice that the record for some unknown reason entirely disappeared, to return of itself again after an interval of several hours. Careful scrutiny at the time of these mysterious disappearances revealed nothing wrong with the arrangements. Subsequently it developed that there had been slight earthquakes in Japan and that a seismograph of surpassing delicacy unconsciously had been created. As might be expected, these results, published in their final form in collaboration with H. G. Gale in 1919, probably stand for all time as an enduring and exact record made by direct measurement not only of the earth's rigidity, but of its viscosity as well. The very involved and complicated tidal computations which were an essential part of the analysis of the results were made by Professor F. R. Moulton and his computing staff.

The most baffling problem of a purely mechanical sort that Michelson ever attempted and one that perhaps did most to wear down his vitality, especially in the later years of his life, was the ruling of diffraction gratings. Such devices in a crude form were first made by Nobert in 1851, but these consisted only of a few thousand lines. L. M. Rutherford, of New York, in 1868 ruled 2-in. surfaces having about 10,000 lines/in., but gratings were first brought to high and useful quality by Henry A. Rowland, of Johns Hopkins University, who succeeded in ruling surfaces 6 in. long containing a total of as many as 100,000 lines and having as the technical measure of their effective usefulness, a resolving power of $15 \times 10^4$. Subsequently, after Rowland's death, his machine has produced gratings of $40 \times 10^4$ resolving power in the fourth order.

Since Rowland gratings were difficult to obtain because of their scarcity, Michelson in 1899 began the construction of a ruling engine of his own, thinking that with the experience that had been gained from his predecessors the task could be accomplished in about six months. Thirty-seven years have since elapsed. The problem still is a problem and still is being carried on.* Michelson did not fail to achieve conspicuous success. In 1907, after eight years of struggle, he produced a 6-in. grating containing 110,000 lines of a perfection measured by $60 \times 10^4$ approximately. In 1915 he achieved the production of both an 8- and a 10-in. grating, containing 117,000 lines, which are still among the most powerful instruments of diffraction that the world possesses, and this in spite of the fact that several other institu-

* Recently Professor H. G. Gale on a redesigned ruling engine has produced gratings with resolving power of $21 \times 10^4$ in the first order. This is a distinct advance in the art since resolving powers theoretically increase in direct proportion to the order.

tions with great resources at their command have likewise engaged in the production of these ruled mirrors. Nothing expresses the years of difficulty, discouragement, and delay in this one problem that may be said to have baffled Michelson, better than his own words tinged as usual with his gentle humor:

> "One comes to regard the machine as having a personality—I had almost said a feminine personality—requiring humoring, coaxing, cajoling even threatening. But finally one realizes that the personality is that of an alert and skillful player in an intricate but fascinating game, who will take immediate advantage of the mistakes of his opponent, who 'springs' to most disconcerting surprises, who never leaves any result to chance, but who nevertheless plays fair, in strict accordance with the rules he knows, and makes no allowance if you do not. When *you* learn them, and play accordingly, the game progresses as it should."

No discussion of Michelson, however brief and inadequate it may be, can fail to comment on the man's artistic side. This artistic side has crept unconsciously into his scientific bibliography in two papers little known. The first, entitled, "Form Analysis," appeared as his 52nd paper in 1906. At this period, Michelson was struggling with the ruling engine and doing some highly mathematical work to develop the theory of a reciprocal relation in diffraction to which his intuition had led him and which he had subjected to experimental verification.[3] He begins his paper on form analysis as follows:

> As a recreation in the midst of more serious work, I have been interested in the analysis of natural forms: and hoping that the results of this somewhat desultory occupation be not deemed too frivolous for so august an occasion [a meeting of the American Philosophical Society], I will venture to present some illustrations and generalizations which have occurred to me. I recognize that the subject is one whose adequate treatment would tax the best efforts of one who combined the insight of the scientist, with the aesthetic appreciation of the painter and the gift of language of the poet—and certainly I am lacking in all three—but especially in the power of adequate expression. I had hoped that my contribution would at least have the merit of originality, but I find that many abler investigators have found a similar delight in this interesting field, and have expounded their ideas with a wealth of poetic imagery and of exquisite illustration such as I cannot hope to emulate."

The paper consists of an elaborate and detailed classification of natural symmetrical forms that occur in strikingly similar fashion in such widely dissimilar objects as vegetables, protozoa, crystals, and even liquids. With a vividness which belies his modest conviction that he lacks in powers of adequate expression, he describes the forms produced by drops of colored liquid falling into another liquid of nearly the same density, and concludes as follows:

> "In designing for the sake of decoration, symmetrical forms are everywhere manifest, and the perception of their mutual relations is indispensable to the student of art. Occasionally, however, there is in decoration a deliberate departure from symmetry, and such a variation may greatly enhance the beauty and effectiveness of the design. We tire of too great uniformity even of agreeable kinds, and the element of variety is as important in art as an occasional discord is in music—its purpose being to heighten the effect of the succeeding harmony.
>
> "One of the great disadvantages of the modern tendency to extreme specialization in research is the loss of companionship of the sister sciences, with the attendant loss of perspective which a more general survey of the whole field of science should furnish. Should we not, then, utilize every opportunity which promises to further their union?
>
> "The geologist, the chemist, the physicist, the mathematician, may and occasionally do meet here on the common ground of crystallography. By a comparatively slight extension, the 'ground forms' of organisms—as Haeckel terms them—may also be included with a corresponding extension of our society of sciences to include zoology and botany.
>
> "Nay, Art will demand a chair at the banquet, and Music and Poetry will also grace the feast."

The other paper to which we wish to refer as so vividly reflecting the artist is entitled "On the Metallic Coloring in Birds and Insects." This paper, the text of which appears to be entirely scientific, calls attention to the fact that the rainbow and the halo are the only cases of prismatic colors in nature (those scattered by individual dewdrops and ice crystals are presumably included). Almost all other cases of color in nature are due to selective absorption, by pigments. However, two other physical methods produce color: diffraction and other types of interference, and reflection from surfaces of metals. Suspecting that the so-called iridescent colors seen in humming birds, certain kinds of butterflies, and a wide variety of bettles and other insects were neither prismatic in character nor due to pigments, Michelson set out to discover which of the other two physical phenomena, interference or

[3] See paper 51, bibliography.

metallic reflection, might be their cause. His conclusion is that with few exceptions these iridescent colors have precisely the same physical attributes as colors reflected from thin metallic films. One noteworthy exception, that of the diamond beetle, was found to have in the iridescent spots upon its wing case, gratings as fine as 2000 lines/in.

In the technic of making optical tests of high precision upon objects of such extreme minuteness Michelson's experimental genius never shone with greater luster, and in the water color paintings of his specimens which he provided for the illustrations in his *Studies in Optics* the artist in him found complete expression. With respect to art in these connections he once wrote:

> "The Aesthetic side of the subject is by no means the least attractive to me. I hope the day is near when a Ruskin will be found equal to the description of the beauties of coloring, the exquisite gradations of light and shade and the intricate wonders of symmetrical forms and combinations which are encountered everywhere."

It is perhaps germane here to relate a story told in connection with a showing of some of his water colors which, with great reluctance he was finally prevailed upon to give some years ago. Physical force almost had been necessary to get him there in person, and while he was there a lady who obviously was overwhelmed with astonishment that a great scientist should be able to produce such charming landscapes, came up to him, and said that she felt he must have made a great mistake when he abandoned art for science. Michelson, with the characteristic grave courtesy that he always achieved when dissenting from another's opinion, replied that he hoped she was mistaken. To his own way of thinking, he said, he felt that he had never abandoned art. It was his conviction that in science alone art was able to find its highest expression. Moulton, in an appreciation of Michelson published in *Popular Astronomy* for June–July, 1931, has clearly caught the spirit of his work:

> "He was unhurried and unfretful, he was never rushed by University duties, he never drove himself to complete a laborious task, he never feared that science, the University, or mankind was at a critical turning point. He never trembled on the brink of a great discovery. . . . There are doubtless many motives that inspire men to scientific achievements. If I have clearly caught the dominant note of his life, Michelson was moved only by the aesthetic enjoyment his work gave him. In everything he did, whether it was work or play, he was artistic. . . . He pursued his modest and serene way along the frontiers of science making new pathways and ascending to unattained heights as easily and as leisurely as though he were taking an evening stroll."

When asked by practical men of affairs for reasons which would justify the investment of large sums of money in researches in pure science, he was quite able to grasp their point of view and cite cogent reasons and examples whereby industry and humanity could be seen to have direct benefits from such work. But his own motive he expressed time and again to his associates in five short words, "It is such good fun." That such a man as he should furnish inspiration for the poet is not at all strange, and two stanzas about him from a ballad written by Edwin H. Lewis[4] on the occasion of the retirement of the late Martin A. Ryerson from the chairmanship of the Board of Trustees of the University of Chicago, should be preserved:

Rude is the minstrel's measure, and rudely he plucks the strings,
But in Ryerson rainbows murmur the music of heavenly things.
Is not this stranger than heaven that a man should hear around
The whole of earth and the half of heaven and see the shadow of sound?
He gathereth up the iris from the plunging planet's rim
With bright precision of fingers that Uriel envies him.
But when from the plunging planet he spread out a hand to feel
How fast the ether drifted back through flesh or stone or steel,
The fine fiducial fingers felt no ethereal breath.
They penciled the night in a cross of light and found it still as death.
Have the stars conspired against him? Do measurements only seem?
Are time and space but shadows enmeshed in a private dream?

But dreaming or not, he measured. He made him a rainbow bar,
And first he measured the measures of man, and then he measured a star.
How tell us how long is the metre, lest fire should steal it away?
Ye shall fashion it now, immortal, of the crimson cadmium ray.

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[4] *University of Chicago Poems* (Univ. of Chicago Press).

How tell us how big is Antares, a spear-point in the night?
Four hundred million miles across a single point of light.
He has taught a world to measure. They read the furnace and gauge
By lines of the fringe of glory that knows nor aging nor age.
Now this is the law of Ryerson and this is the price of peace—
That men shall learn to measure or ever their strife shall cease.

## Bibliography of Publications of Albert Abraham Michelson*

### *Books*

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### *Articles*

Papers listed under the same number are identical except when distinguished by a sub-classification, in which case the nature of the differences is explained.

1. (*a*) "On a Method of Measuring the Velocity of Light," Am. J. Sci. (3) **15**, 394–95 (1878); (*b*) "Velocity of Light (Preliminary Announcement)," Nature **18**, 195 (1878), differs from (*a*) in the addition of a paragraph.

2. "Experimental Determination of the Velocity of Light," Proc. A. A. A. S. **27**, 71–7 (1878).

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6. (*a*) "The Relative Motion of the Earth and the Luminiferous Ether," Am. J. Sci. (3) **22**, 120–29 (1881); (*b*) Comptes rendus **94**, 520–23 (1882), a shortened account of (*a*) with a correction.

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* Acknowledgments are due to Ardis T. Monk for the accurate revision of this bibliography from one previously published in J. O. S. A. **18**, 151 (1929).

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# The Mass-Spectrograph and Its Uses

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LONG before the term *mass-spectrograph* was invented experiments had been carried on in an effort to learn something of the nature of positive and negative rays. The famous experiments of J. J. Thomson and W. Wien marked a great step forward in our understanding of atomic physics. By the application of electric and magnetic fields to fast flying particles in a discharge tube these experimenters were able to measure the velocities as well as the ratio $e/m$ of the charge to mass both of the cathode rays, which turned out to have always the same value of $e/m$, and of some of the positive particles, for which $e/m$ was not always the same.

In 1919, after some experiments by Thomson had indicated that all atoms of the element neon might not be identical, Aston constructed an improved instrument for studying such rays. Because of the close analogy of this apparatus with the optical spectrograph and the similar "spectrum" of sharp lines obtained on a photographic plate when exposed to the positive rays issuing from it, Aston called the instrument a "mass-spectrograph." He originally intended the name to apply only to this particular design but it has grown to mean, rather loosely to be sure, almost any kind of apparatus that will distinguish between particles of different $e/m$. In this paper, therefore, any apparatus which through some combination of electric or magnetic fields, or both, is able to sort out charged particles according to their $e/m$—ratio will be called a mass-spectrograph.

## 1. Components of a mass-spectrograph

The primary purpose of any mass-spectrograph is to identify or measure the ratio of charge to mass of a small free particle or ion. As a first approach to the subject then, one asks what simple measurable properties does such a particle have, and immediately such things as velocity, momentum, energy, and acceleration suggest themselves. From a knowledge of any two of the three quantities velocity, energy, and momentum the mass is readily calculable. Hence all the well-known mass-spectrographs concern themselves with the measurement of two of these quantities. Always, as will be shown presently, the charge $e$ of the particle appears as an unknown in at least one of the two quantities and as a result only the ratio $e/m$ is found.

The work of Millikan and others has shown that the charge is always an integral multiple of one elementary charge. Years of experience in the study of ionization of matter to produce the charged particles has yielded sufficient information to enable one to determine the number of elementary charges the ions carry under a given set of conditions. Fortunately, in practice, there are very few possible choices and hence this identification of the charge is a simple matter in most cases. Once it has been decided whether a particular ion has one, two or some such integral number of charges then the mass $m$ obviously can be calculated from the $e/m$ ratio. In most physical measurements the ratio of two similar quantities may be determined with far greater accuracy than the absolute value of either quantity and so it is in this field. Masses are usually expressed in terms of the most abundant isotope of oxygen, the latter being assigned a value of exactly 16 on an arbitrary scale. It is to be remembered, however, that fundamentally the mass-spectrograph determines only the ratio $e/m$ and must rely on other data for the magnitude of the charge and hence of the mass.

Since the theory of the mass-spectrograph resolves itself into the theories of measuring the velocity, momentum and energy of free, charged particles, a simple outline of the latter will now be given.

1. *The energy filter.* Any device that sorts out from a stream of particles of widely different energies a fraction having within relatively narrow limits the same energy may be called an *energy filter*. The most useful type involves the application of an electric field perpendicular to the direction of motion of the ions as shown by *Ia* in Fig. 1. For simplicity let us consider the circular type. The ions are projected between the plates of a cylindrical condenser and those that describe a circular path of radius $R$ satisfy the

relation $mv^2/R=Ee$, or

$$mv^2/2=REe/2, \tag{1}$$

where $E$ is the field strength. Consequently all those ions having energies given by $REe/2$ describe a circular path which allows them to escape through the exit slit. Those having greater energies will progress toward the outer electrode and those of lesser energies will deviate toward the inner electrode. In the plane of the exit slit, therefore, will be found a kind of energy "spectrum," the slit being so placed that all ions of energies different from the desired one are stopped. When the angle through which the ions are deflected is small, plane parallel electrodes are sometimes used. It happens that for an angle of 127° a focussing property comes into play about which more will be said later. It is clear then that such a device constitutes an energy filter which allows only a few definite energies to pass through according to whether the ions carry 1, 2, 3, etc. elementary charges.

Another method of securing ions homogeneous in energy is illustrated by *Ib* in Fig. 1. This is strictly speaking not a filter at all but for convenience will be classed under this heading. It consists merely in allowing ions which are initially at rest, or practically so, to fall from a source $S$ through a definite difference of potential $V=Ed$ thereby gaining energy given by

$$mv^2/2=eV. \tag{2}$$

All similarly charged ions will emerge from this arrangement with practically the same energy.

2. *The momentum filter.* A beam of ions homogeneous in momentum may be obtained by projecting a heterogeneous beam through and at right angles to a uniform magnetic field, as shown in Fig. 2. Since the force due to the field

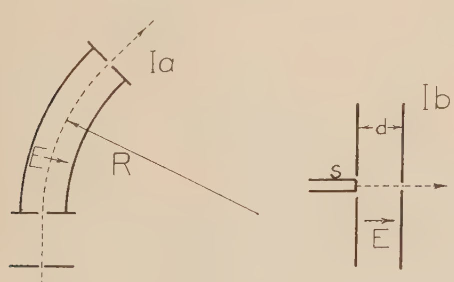


FIG. 1. Two methods of obtaining ions of uniform energy.

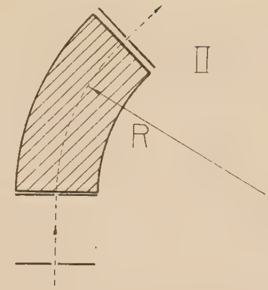


FIG. 2. A momentum filter. In all figures a shaded area represents a magnetic field perpendicular to the plane of the drawing.

$H$ is always perpendicular to the motion, the path described is a circle and the force equation is $mv^2/R=Hev$, or

$$mv=RHe. \tag{3}$$

Evidently all ions of a given charge $e$ will emerge from this device with the same momentum. In the plane of the exit-slit will be found a momentum "spectrum," the slit itself acting as a selector for the range of momentum desired in the ion beam. In some arrangements a photographic plate replaces this slit and the distribution of momentum in the ion beam is recorded as a function of position on the plate.

3. *The velocity filter.* One type of velocity filter makes use of an electric and a magnetic field simultaneously, the directions of the fields and the direction of projection of the ion beam being mutually perpendicular. This method is illustrated by *IIIa* in Fig. 3. The magnetic field is of such a sense that the force which it exerts on the charged particles is opposed to that due to the electric field. If these two forces just balance each other for a particular ion, it will pass through the apparatus in a straight line and emerge from the exit-slit. This condition is expressed by the relation, $eE=Hev$, or

$$v=E/H. \tag{4}$$

An important characteristic of this arrangement is that the velocity is independent of the charge and mass of the ion. It was by this means that Wien and Thomson measured the velocities of ions and electrons many years ago. In using the apparatus as a velocity filter care must be taken to adjust the absolute magnitudes of the fields so that the exit-slit is at the point of greatest

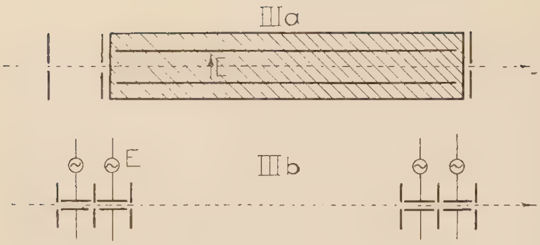


FIG. 3. Two types of velocity filters.

resolving power in the system of rather complicated orbits which the particles having other than the chosen velocity describe.

Another scheme for a velocity filter is shown by *IIIb*, in Fig. 3. The theory for this arrangement has been worked out by Smythe.[1] The incoming particle traverses two regions where transverse alternating electric fields are applied. Each pair of condensers acts as a shutter by allowing particles to pass only during a small part of the cycle. Only those particles get through both shutters whose velocity and phase satisfy certain relations and hence the device may be used as a velocity filter. The arrangement is analogous to the toothed wheel method of Fizeau for measuring the velocity of light and similar experiments for measuring the velocity of neutral molecules of a gas.

4. *Focussing properties*. In our discussion of the various filters no mention was made of the effect of rays entering the device at angles slightly inclined to the central ray or of the effect of the finite width of the slits employed. Actually there are many geometrical proportions for which these devices permit of a focussing action. For example the momentum filter of Fig. 2 gives greatly improved results if the arc through which the ions are deflected is 180°; diverging rays from the first slit will then converge toward the second, thus improving the intensity as well as the resolving power of the arrangement. This property is readily understood if it be remembered that all orbits in the magnetic field are circular and rays entering slightly inclined to the central ray have the centers of their arcs displaced above or below the plane of the slits. This displacement changes the length of the chord cut out by the plane of the slits by a very small amount as

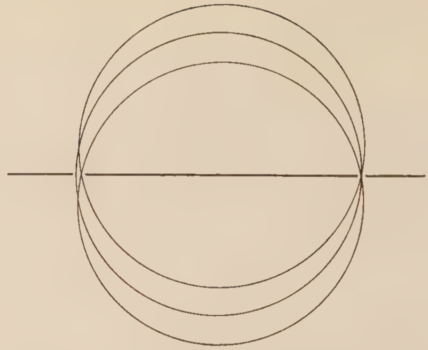

FIG. 4. Illustrating the focussing effect of ions of the same velocity turned through 180° in a magnetic field.

shown in Fig. 4 and a good although not perfect focussing action is achieved.

In the case of an energy selector in which the radial field has been made proportional to $1/R$, computations[2] have shown that the best focus occurs at an angle of 127°. The theory of these effects becomes complicated in many cases and the reader is referred to the original literature for details. It may be well to mention that a combination of these filters sometimes exhibits a focussing property when none exists for the units used separately.

5. *Sources of ions*. Several methods have been developed for producing beams of positive rays suitable for study with the mass-spectrograph. The low-voltage discharge maintained by electrons of controlled speed emitted from a heated cathode has been used extensively to produce ions in gases and vapors. This source permits the investigation of many phenomena as a function of the electron velocity. Canal rays from a high-voltage discharge are usually used when one is not interested in how the ions are formed. This method gives a wide distribution of energies in the ion beam, breaks down complicated molecules into simple atomic ions, and even sputters or vaporizes some of the solid material in the electrodes to give ions not ordinarily found in gases. Substances not readily volatilized may be investigated in this way by impregnating the anode with the material and running a high-voltage discharge in some permanent gas. This is sometimes called the *method of anode rays*.

Some salts and minerals when heated to in-

[1] W. R. Smythe, Phys. Rev. **28**, 1275 (1926).

[2] Hughes and Rojansky, Phys. Rev. **34**, 284 (1929).

candescence emit ions of those metals having low ionizing potentials. In practice the material is usually deposited on a metallic strip which may be heated by current from an external source. The ions are then accelerated in a region of high vacuum. Some solids have been found to emit positive ions when subjected to heavy electron bombardment but in general this source is of little use. Recently certain types of high-frequency vacuum sparks have been found to yield multiply charged ions in copious quantities.

6. *Methods of detection.* Having discussed the production of ion beams and the methods of selecting those components homogeneous in velocity, energy or momentum, the question of their detection naturally arises. The two principal devices for recording the final analyzed products are the photographic plate and a current- or charge-measuring instrument. To measure small charges or currents an electrometer of the most sensitive type is suitable. In recent years certain vacuum tube arrangements have been developed that are even more sensitive and perhaps admit of more refined measurements of current than any other instrument of this type. Direct measurement of the currents in ion beams usually is the most reliable method of determining their relative intensities and this is one of the chief advantages of this method of detection.

High-speed ions when allowed to strike a photographic plate act in much the same way as a light beam; a trace is left whose position and intensity are readily measured after the plate has been developed in the usual way. This method has a great advantage in that it leaves a permanent record which may be studied at leisure and measured with great accuracy. The density of the trace increases with time of exposure so that weak effects may build up to a visible trace if the exposure is long. The disadvantages of the method are that the plate is insensitive to slow ions and the intensity of the incident ion beam is an uncertain function of the density of the trace produced on the photographic plate.

There are other methods of detection not extensively used such as the fluorescent screen which renders the spots where streams of ions strike visible to the eye. Another scheme depends on the fact that the relatively heavy positive ion moves with much less speed than electrons of the same energy and therefore one such ion may neutralize the space charge of thousands of electrons in the region of a filament where the electron emission is limited by space charge; hence one looks for an increase in electron emission as a criterion for the presence of positive rays.

7. *Vacuum systems.* In the analysis of any type of ionic rays it is desirable to have the particles traverse their entire trajectory with as few collisions with molecules along the way as possible. This means that the residual gas in the analyzing chambers should be maintained at the lowest pressure which is conveniently attainable. On the other hand, if the ions are produced in some sort of gaseous discharge the pressure there must be sufficient to give a strong source of ions. To satisfy both of these conditions some form of differential pumping is usually employed. The regions where high- and low-vacuum conditions are desired are separated by diaphragms pierced by fine holes or slits to allow a portion of the ion beam to pass, while fast pumps attached to the analyzing chamber maintain there the low pressure desired.

## 2. Types of mass-spectrographs

After this discussion in some detail of the various essential parts of the mass-spectrograph we are now ready to consider the choice and arrangement of these components in the various well-known types. It is obvious that a great variety of forms may be built by putting together in different combinations the units described. In what follows attention will be confined to instruments that actually have been built and whose utility has been demonstrated in useful experiments.

1. *The parabola method of J. J. Thomson.* In this famous set-up the energy filter *Ia* and the momentum filter *II* are applied simultaneously to an ion beam but in such a way that the deflections produced by these two units are at right angles; that is, the electric field $E$ and magnetic field $H$ are parallel. Let the direction of propagation of the undeflected particles be along the $z$-axis and the direction of the two fields be parallel to the $x$-axis. The usual arrangement provides for a screen at some distance from the region of the fields as shown in Fig. 5. If the angular deflection

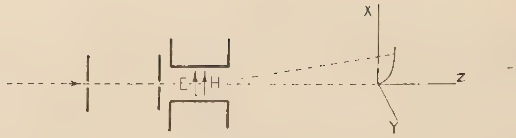


FIG. 5. The J. J. Thomson parabola method of analysis.

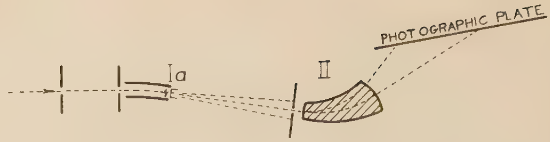


FIG. 6. The Aston mass-spectrograph.

is small, as is the case in most instruments, the $x$- and $y$-deflections are given by the following relations which may be found in almost any elementary text:

$$x = AEe/mv^2, \quad y = BHe/mv.$$

Here $v$ is the velocity of the incident ion and $A$ and $B$ are constants which depend on the geometry of the apparatus. It will be noticed that for a particular $e/m$ the energy and momentum are inversely proportional to $x$ and $y$ respectively. Moreover,

$$y/x = (BH/AE)v \tag{5}$$

provides a measure of the velocity, and

$$y^2/x = (B^2H^2/AE)e/m, \tag{6}$$

provides a measure of the $e/m$ of ions arriving at a point $(x, y)$ on the screen. From Eq. (6) it is seen that all ions having the same $e/m$ will lie along a single parabola regardless of their velocities.

The usual source of ions for this apparatus consists of canal rays from a 20 to 50-kilovolt discharge maintained in the gas to be investigated. The photographic plate has been used almost exclusively as the detecting device. This arrangement for studying mass-spectra and the formation of ions in discharges yields more information, perhaps, than any other because of its ability to measure both $e/m$ and the velocity. Its disadvantages are a lack of any focussing properties and a limited sensitivity, since the ions are spread out over a long curve thus making the density at any one place rather small.

2. *The Aston mass-spectrograph.* By far the most famous type of instrument in this group and justly so is that of Aston. His method is to send anode or canal rays from a discharge tube through first an energy analyzer *Ia* and then a momentum analyzer *II*. By placing these units so that the deflections produced were in opposite directions (Fig. 6), he found that a velocity-focussing property was achieved by the combination if the photographic plate used for a detector was placed in a certain position. The theory of this arrangement appears in so many books and the methods of using the instrument are so well described by Aston[3] that no further treatment need be given here.

3. *The Dempster method of analysis.* Another arrangement which has been used widely was employed originally by Classen to measure the $e/m$ of the electron and first adapted to positive rays by Dempster.[4] He chose the combination $(Ib+II)$ arranged as shown in Fig. 7. Ions of constant energy obtained by accelerating them to a high velocity from a state of very slow motion were passed through a momentum filter with the 180° focussing property discussed in Sec. 1–4. The ions were emitted from hot filaments coated with suitable materials or were drawn from a low-voltage discharge in gases. The detecting device used in most cases was the electrometer. This method has found its widest use in the study of products of ionization and ionizing potentials in gases, an example of which will be described later. More instruments of this general character have been built, and more people have used them, than any of the other models. In the hands of Smyth, Hogness, Kallmann and many others it has aided in the solution of many baffling problems in physics and chemistry.

4. *A high-intensity mass-spectrograph.* A low resolving power, high intensity instrument devised by the author[5] was found useful for certain studies. The choice in this case was $(Ib+IIIa)$. The attainment of high intensities is not attributable to this choice in itself but rather to the novel arrangement of the magnetic field and source of ions. In most other designs the

[3] F. W. Aston, *Mass-Spectra and Isotopes* (Longmans, Green, 1933).
[4] Dempster, Phys. Rev. **11**, 316 (1918).
[5] Bleakney, Phys. Rev. **34**, 157 (1929); **40**, 496 (1932).

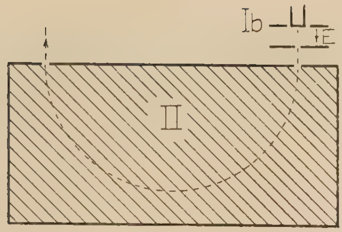


FIG. 7. Dempster's method.

magnetic field is derived from an iron electromagnet whose poles must be placed close together in order to obtain a strong uniform field and this necessitates slits only a few millimeters long in most cases. In the instrument under consideration, however, the field was supplied by a long solenoid within which the whole apparatus was placed and hence slits several centimeters long could be used without loss of resolving power. An electrometer was used as a detecting instrument and hence the long slits contributed greatly to the size of the current to be measured. The source of ions was the narrow ribbon-like discharge just outside the entrance slit produced by a stream of electrons shot down the tube with constant velocity parallel to the magnetic field, which served to define the electron beam and concentrate the discharge in a very narrow region. Other instruments were later constructed in which the momentum filter *II* was substituted for the velocity filter *IIIa* to take advantage of its better focussing properties.

It was found that either of these combinations could be operated at gas pressures so low that only a minute fraction of the ions formed ever collided with other molecules before reaching the final collector. For this reason it was admirably adapted to the study of so-called primary ionization in gases. The remarkable sensitivity of the design permits the study of very rare isotopes of the lighter elements; in favorable cases isotopes existing to the extent of only 1 part in $10^6$ can be detected. The somewhat low resolving power, due to the limitations on the size of the instrument and the magnetic field, is the chief disadvantage of this type.

5. *The Bainbridge high-precision instrument.* An apparatus for measuring the masses of isotopes with high precision was designed by Bainbridge[6] by using the combination (*IIIa* +*II*). Ions from a high-voltage discharge were shot first through a velocity filter and then through a momentum analyzer where they were recorded on a photographic plate. The momentum analyzer was of the 180°-type. This apparatus has some excellent features. One is that the ions fall perpendicularly on the photographic plate and produce there a trace which is symmetrical in density about the center of the line, thus allowing accurate measurements to be made of line separations even though the lines differ in intensity. Another important advantage is that the mass is a linear function of the distance along the plate. Some of the most accurate comparisons of isotopic masses have been made with this instrument, the probable error being in favorable cases only about 1 part in $10^5$. Possibly one disadvantage of this set-up is that, because of the use of the velocity filter, the ions which fall on the plate do not originate in the same region of the discharge; consequently, relative abundance measurements are difficult to obtain with any accuracy.

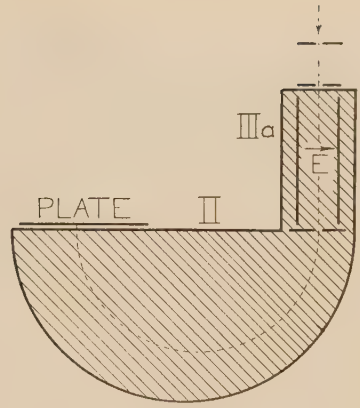


FIG. 8. The Bainbridge high-precision instrument.

6. *A mass-spectrograph without the use of magnetic fields.* It is readily seen that the combination (*IIIb*+*Ia*) is sufficient to determine $e/m$ and no magnetic field is involved in the design. Such a system was proposed by Smythe[1] and constructed by Smythe and Mattauch.[7] This arrangement seems to have many inherent advantages in the way of resolving power and ability to compare accurately ions of widely

[6] Bainbridge, J. Frank. Inst. **215**, 509 (1933).

[7] W. R. Smythe and J. Mattauch, Phys. Rev. **40**, 429 (1932).

different masses. It is a rather delicate piece of apparatus to construct, however, and so far has been little used.

7. *Other types.* Obviously all the possible combinations of the units necessary for a mass-spectrograph have not been exhausted in the types that have been described. Bartky and Dempster[8] discussed the theory of the simultaneous application of *Ia* and *II*, the electric field being made proportional to $1/R$ and perpendicular to the magnetic field. Bondy and Popper[9] built an apparatus according to this plan and found that it worked satisfactorily. The famous "cyclotron" invented by Lawrence[10] for the production of ions of very high energy might be used as a mass-spectrograph, since it sorts out a particular $e/m$. Still other types have been used for the measurement of the $e/m$ of the electron. It should also be mentioned that some proposed arrangements cannot be classified as a system of filters at all. In this short review it is impossible to go further into the details of these various designs.

### 3. Examples of uses of mass-spectrographs

1. *The isotopic constitution of an element.* A beautiful example of the use of the mass-spectrograph to determine the isotopic constitution of an element is that of Aston's analysis of tin.[11] Some tin tetramethyl was introduced into the discharge in this case. The mass-spectra are reproduced in Fig. 9. On the original negative of plate (*c*) can be found traces of eleven isotopes of tin having mass numbers 112, 124, and 114 to 122 inclusive, the two strongest lines being 118 and 120. On plates (*a*) and (*b*), in addition to the series of tin ions, lines appear for the xenon ions 132, 134, and 136 and, between these, the two strong tin monomethyl lines $Sn^{118}CH_3$ and $Sn^{120}CH_3$ of mass numbers 133 and 135 respectively. This whole group gives the appearance of a regular sequence and careful examination by Aston confirmed this conclusion. Now the masses of the xenon isotopes, as well as those of carbon and hydrogen, had already been determined by Aston with considerable accuracy:

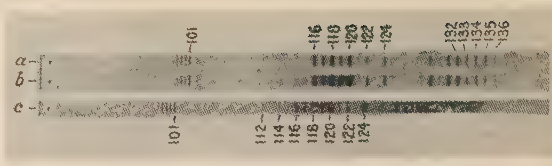

FIG. 9. Mass-spectra of tin (*Aston*).

| Isotope | Mass |
|---|---|
| $Xe^{134}$ | 133.929 ±0.012 |
| $Xe^{136}$ | 135.929 ±0.012 |
| $C^{12}$ | 12.0036±0.0003 |
| $H^1$ | 1.0078±0.0001 |

Since $Sn^{120}CH_3$ falls midway between $Xe^{134}$ and $Xe^{136}$ its mass must be 134.929. Subtracting off the mass of $C^{12}$ and three hydrogens we have left 119.902±0.012 as the mass[12] of $Sn^{120}$. Further analysis showed that the tin isotopes formed a regular equally-spaced sequence separated from each other, within the errors of measurement, by exactly one mass unit. Hence the masses of all the tin isotopes are found with considerable accuracy by adding or subtracting the appropriate integer to the mass of $Sn^{120}$. These masses are of course all determined on the assumption that $O^{16}$ has exactly the value 16.

By photometric methods Aston was able to estimate the intensity of the tin lines and so arrive at the relative abundance of these isotopes. The technique of determining the relative abundance by photometry is described in Aston's book[3] to which the reader is referred if interested in the details. The method is analogous to that of measuring the relative intensity of spectral lines by means of the photographic plate and is beset with the same sort of difficulties. The result of the intensity analysis for the tin isotopes was as follows:

| Mass No. | 112 | 114 | 115 | 116 | 117 | 118 |
|---|---|---|---|---|---|---|
| Abundance (%) | 1.07 | 0.74 | 0.44 | 14.19 | 9.81 | 21.48 |

| Mass No. | 119 | 120 | 121 | 122 | 124 |
|---|---|---|---|---|---|
| Abundance (%) | 11.02 | 27.04 | 2.96 | 5.03 | 6.19 |

Multiplying each mass number by its fractional abundance and adding these products gives the *mean* mass number 118.82. But we have already found that each isotope lacks 0.098 mass units of being an exact integer. By subtracting this amount from the mean mass number we obtain

[8] Bartky and Dempster, Phys. Rev. **33**, 1019 (1929).
[9] Bondy and Popper, Ann. der Physik **17**, 28 (1933).
[10] Lawrence and Livingston, Phys. Rev. **40**, 19 (1932).
[11] Reference 3, p. 132.

[12] Aston gives for this value 119.912. On checking over the figures it was found that he had made a slight error in the computations. Recent revisions of the masses of C and H are negligible in this computation.

118.72 for the mean atomic weight on the Aston scale of $O^{16}=16$. To get the *chemical* atomic weight, which is based on the assumption that the mean atomic weight of the oxygen isotopes is exactly 16, we must subtract two parts in ten thousand, which gives 118.70 for the chemical atomic weight of tin. This result agrees exactly with the accepted value obtained by chemical methods. Similar analyses have been made by Aston for a large number of the elements.

2. *High-precision measurements of isotopic masses.* Perhaps the most accurate way of measuring the relative masses of atoms is the so-called *doublet method* used extensively by Aston and Bainbridge. As an illustration a description will be given of Bainbridge's experiment to determine the relative masses of helium, hydrogen, and deuterium, as the heavy isotope of hydrogen is now called. The method as Bainbridge used it consists in photographing two ions whose masses differ by only a small fraction of one mass unit. The two traces are obtained simultaneously under identical conditions. A measurement of the interval of separation and the dispersion of the instrument in that region are the only data required to calculate the mass difference. In Fig. 10 are shown[13] the doublets $He^{++}-H_2^+$, $(HeH)^+-(D_2H)^+$, and $(HeD)^+-D_3^+$. Bainbridge had already calibrated his instrument and found the dispersion, or variation of $m/e$ with distance along the plate, to be quite linear. Small intervals on the plate could therefore be translated to equivalent mass units with high precision provided the charges are precisely known. Consider the interval between $He^{++}$ and $H_2^+$ shown in Fig. 10*b*. Let $m_{He}$ and $m_H$ be the masses of the neutral helium and hydrogen atoms respectively, and let $m_e$ be the mass of the electron. Let $\Delta m/e$ be the interval in question. Then $\Delta m/e=(2m_H-m_e)/e-(m_{He}-2m_e)/2e$ and

$$m_{He}/m_H=4-2\Delta m/m_H. \qquad (7)$$

The average value of $\Delta m$ found by Bainbridge from measurements of Fig. 10*b* was 0.014470 $\pm 0.000020$. By substituting this in the formula together with an approximate value of $m_H$, since the latter enters only as a correction term, the

[13] Bainbridge, Phys. Rev. **43**, 104 (1933); **44**, 57 (1933).

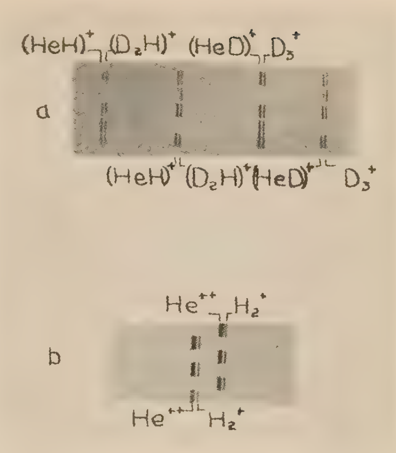


Fig. 10. Mass-spectra of H, D and He (*Bainbridge*).

helium to hydrogen ratio is obtained:

$$m_{He}/m_H=4-2\times 0.014470/1.008$$
$$=3.97129\pm 0.00004.$$

It will be seen that a very precise value for the mass $m_H$ entering in the correction term is not necessary and therefore future refinements of the ratio H to $O^{16}$ or He to $O^{16}$ will not appreciably affect this fine result. In a similar manner Bainbridge found the ratio He/D from the mass-spectra shown in Fig. 10*a*:

$$He/D=1.98753\pm 0.00004.$$

The method can be extended to build up ratios between different elements until a system of isotopic weights is achieved.

3. *Products of ionization in polyatomic molecules.* One of the first problems to which the mass-spectrograph was applied was a study of the nature of positive rays and their relation to the different gases used in the discharge. Evidently here was a powerful tool for the investigation of the ways in which complicated molecules could be broken up, what charges the different fragments carried, and the energy required to produce the different types of ions. From the early experiments of Thomson with his unique parabola method to the present day the study of positive and negative rays by means of the mass-spectrograph has thrown a great deal of light on the conduction of electricity through gases. As a typical example of this kind

of research let us consider briefly a study of the triatomic molecule $CS_2$ as made by Smyth and Blewett.[14] The apparatus used was of the Dempster type (Sec. 2—3), with some modifications to allow differential pumping from the filament chamber in order to reduce thermal dissociation to a minimum. The source of ions was a low-voltage discharge with electrons of constant and controllable velocity. Fig. 11 shows the mass spectrum obtained in the region of interest when the bombarding electrons had fallen through a difference of potential of 60 volts. The only ions carrying a single positive charge which one might expect to appear from a direct impact of an electron with a $CS_2$ molecule are $CS_2^+$, $CS^+$, $C^+$, $S_2^+$, and $S^+$ and, of these five possibilities, four actually are observed. The fact that considerably more energy is required to produce $C^+$ than any of the others and the absence of $S_2^+$ are arguments in favor of a straight line molecule S—C—S with the carbon in the middle. The case of $CS_2$ is typical of most of the molecules yet studied in that by far the most likely process is simply the removal of one electron with the rest of the molecule left intact. It is of interest of course to find the minimum electron energy required to produce each of these ions. The results are given in Table I

TABLE I. *Ionization processes in carbon disulphide.*

| Ion observed | Appearance potential | Probable process | Calculated minimum energy required |
|---|---|---|---|
| $CS_2^+$ | 10.4±0.2 volts | $CS_2 \rightarrow CS_2^+$ | — |
| $S_2^+$ | Not observed | | |
| $CS^+$ | 14.7±0.5 | $CS_2 \rightarrow CS^+ + S$ | — |
| $S^+$ | 14.0±0.5 | $CS_2 \rightarrow CS + S^+$ | — |
| $C^+$ | 21.5±1.0 | $CS_2 \rightarrow C^+ + S + S$ | 21.4 |
| | In thermally dissociated gas | | |
| $CS^+$ | 10.6±0.3 | $CS \rightarrow CS^+$ | — |
| $S_2^+$ | 10.7±0.3 | $S_2 \rightarrow S_2^+$ | — |

where it will be seen that in only one case is it possible to check these data by computations from thermo-chemical and spectroscopic information. Only the primary products of ionization have been discussed here, but everyone who has delved into this field knows that there are many complicated secondary reactions. If the pressure of the gas is high enough to allow many collisions

[14] H. D. Smyth and Blewett, Phys. Rev. **46**, 276 (1934).

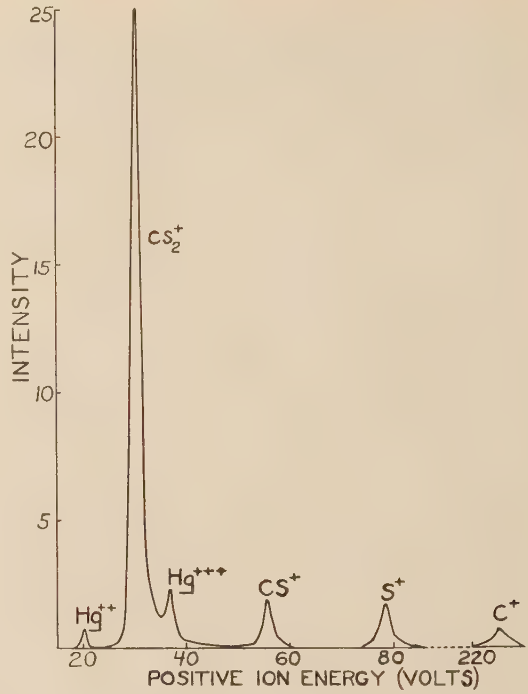


FIG. 11. Mass-spectrum of ions produced in $CS_2$ by 60-volt electrons (*Smyth and Blewett*).

to take place between neutral molecules and ions before they are analyzed, attachments or clusters may form, or the charge may be transferred to another atom or molecule. Collisions may result in the original ions being scattered out of the beam and the probability of scattering is in general different for different kinds of ions. All of these effects have been studied with the mass-spectrograph but a detailed description of the results are beyond the scope of this paper.

4. *Probability of ionization and atomic ionization potentials.* The probability of ionization by electron impact is usually defined as the number of ions formed per electron per unit length of path and unit pressure at some stated temperature when the conditions are such that the probability of making more than one collision is negligibly small. The apparatus best suited to this field of investigation is the high intensity mass-spectrograph described (Sec. 2—4). The example chosen to illustrate this type of work is the analysis of caesium by Tate and Smith.[15] The apparatus was modified to allow the temperature of the ionization chamber to be raised

[15] Tate and Smith, Phys. Rev. **46**, 773 (1934).

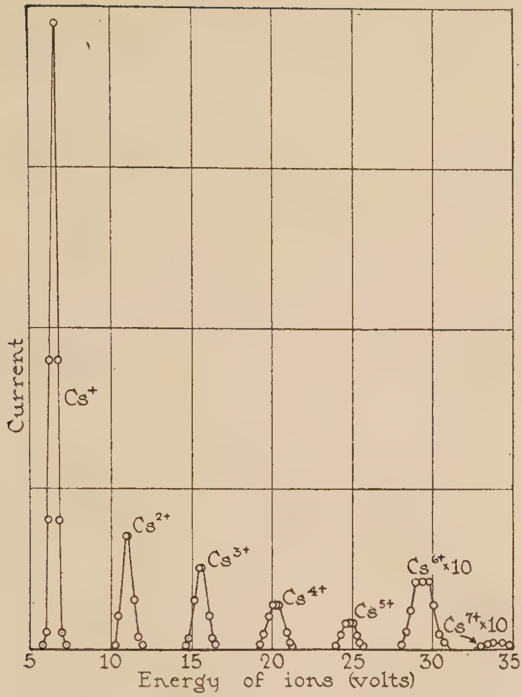


FIG. 12. Multiply charged ions produced in caesium by 700-volt electrons (*Tate and Smith*).

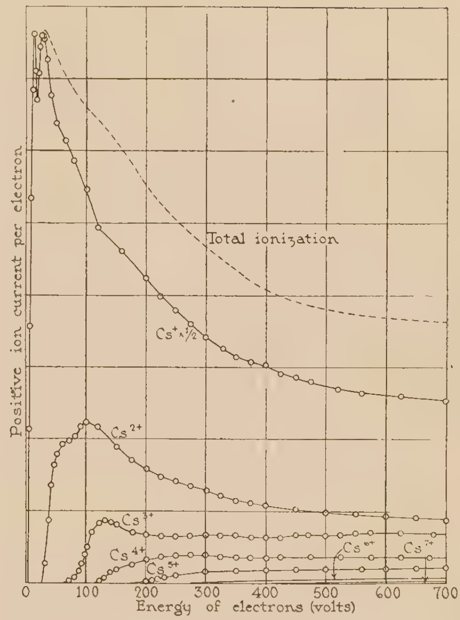


FIG. 13. Probability of ionization in caesium (*Tate and Smith*).

to the point where the vapor pressure of caesium was sufficient to give the desired results. A resulting mass-spectrum is shown in Fig. 12. A study of the heights of these peaks as a function of the bombarding energy gives the relative probabilities of ionization as shown in Fig. 13. The ionization potentials at which these ions first appeared were found to be:

| Ion | $Cs^+$ | $Cs^{2+}$ | $Cs^{3+}$ | $Cs^{4+}$ | $Cs^{5+}$ | $Cs^{6+}$ | $Cs^{7+}$ |
|---|---|---|---|---|---|---|---|
| Volts | 3.88 | 27.4 | 62 | 113 | 117 | 275 | 410 |

It is to be emphasized that these ions are produced in every case as the result of a single blow. That as many as seven electrons can be knocked off of an atom at one shot is a remarkable fact which is proved by the high energy required and by the linearity of the effect with pressure. The theory of ionization probability is extremely complicated and only in the simplest cases have approximate results been worked out. The agreement with the experimental work is as good as can be expected considering the approximations made in the theoretical solution of the problem.

5. *Chemical analysis.* In the last few years the mass-spectrograph has been found to be of great value in the chemical analysis of certain substances which were otherwise very difficult to investigate. This is especially true whenever the relative concentration of isotopes is a factor in chemical reactions. The advantages of this method over most others are the reliability of the data, great sensitivity, and the relative freedom from error due to the presence of large amounts of impurities.

A good illustration of such chemical analysis is to be found in the study of the equilibrium constant between hydrogen and deuterium as a function of the temperature. The analyses of samples prepared by several chemists[16] were carried out by the author with the apparatus described in Sec. **2**—4. The interchange of the hydrogen isotopes in the formation of molecules may be indicated by the formula $H_2+D_2 \rightleftarrows 2HD$. After this reaction comes to equilibrium the number of each of the three types of molecules will remain constant with time. If we use parentheses about a symbol to indicate the number of that type of molecule, then by definition the *equilibrium constant* is given by

[16] Gould, Bleakney and Taylor, J. Chem. Phys. **2**, 362 (1934); Rittenberg, Bleakney, and Urey, J. Chem. Phys. **2**, 48 (1934).

$$K=\frac{(HD)^2}{(H_2)\cdot(D_2)}. \quad (8)$$

This "constant" is independent of the concentration but is a function of the temperature. If the combination of $n_1$ atoms of hydrogen with $n_2$ atoms of deuterium to form the three kinds of molecules was purely a matter of chance then $K$ could be easily calculated since there are $n_1 \cdot n_2$ different ways of forming HD, $n_1(n_1-1)/2$ different ways of forming $H_2$, and $n_2(n_2-1)/2$ different ways of forming $D_2$. Putting these in the relation for the equilibrium constant gives

$$K=\frac{(n_1n_2)^2}{\dfrac{n_1(n_1-1)n_2(n_2-1)}{4}}=4,$$

if unity is neglected in comparison with the large numbers $n_1$ and $n_2$. This is the value of $K$ to be expected if the formation of all three molecules were equally likely, but actually there are slightly different energies released in their formation and hence $K$ is a function of temperature. The problem of determining this function has been solved theoretically[17] but the argument is too involved to be presented here. Suffice it to say that at high temperatures, where the differences in the energies of formation are small in comparison with the kinetic energy of the molecules, $K$ does approach the value 4 asymptotically; but at low temperatures the value falls very rapidly. It is naturally of great interest to test this theory by experiment.

After a great many trials it was found that equilibrium could be established in the presence of chromium oxide as a catalyst. In the absence of any catalyst the reaction immediately stopped so that the mixture could be analyzed in the mass spectrograph at leisure to find the relative numbers of $H_2$, HD and $D_2$. In this way the value of $K$ was found for samples prepared at several different temperatures. The results are shown in Fig. 14 where the plotted points represent experimental data and the curve represents the variation of $K$ with temperature as calculated theoretically from the quantum mechanics. It will be seen that experiment and theory are in good agreement.

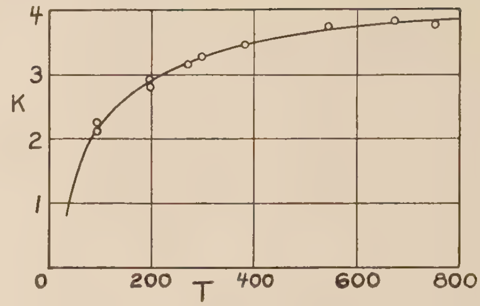


FIG. 14. Equilibrium constant of the hydrogen-deuterium reaction as a function of temperature (*Bleakney*).

6. *Other uses.* In the five examples just described an attempt was made to illustrate only the most important problems to which the mass-spectrograph has been applied. There are of course many other applications but lack of space prevents any more than mentioning a few of them here. The mass-spectrograph has been used to separate permanently the isotopes of some of the alkali metals; the resulting quantities are small but sufficient for certain disintegration studies. Some sort of analysis is often used to separate high-velocity particles in artificial disintegration experiments in order to determine which kind of projectile is responsible for observed effects, and once an ejected particle has been identified the argument is reversed and the instrument used to measure the momentum with which the particle is projected from the nucleus. Many experiments involving absorption or angle of scattering of positive ions require a mass analysis to clarify the results. It is also apparent that all the experiments involving electron impact can be repeated using positive ions as projectiles, and again the mass spectrograph is indispensable for a clear understanding of the observations.

Although only a bird's-eye-view of the subject under consideration has been given in this short paper, the author hopes that it will provide an organized account of a particular field of research broad enough in view and simple enough in character to be of interest and value to undergraduate students of physics as well as to others.[18]

It is a pleasure to acknowledge many sug-

[17] Urey and Rittenberg, J. Chem. Phys. **1**, 137 (1933).

[18] For further reading see: H. D. Smyth, Rev. Mod. Phys. **3**, 347 (1931); Mattauch, Phys. Zeits. **35**, 567 (1934).

gestions from my colleagues at Princeton University.

## Appendix

*A theorem concerning the mass-spectrograph.* The following theorem, which the author has not seen in print, is illuminating from the pedagogical standpoint.

The manner in which the values of $m/e$ vary with the electric and magnetic fields may be derived quite generally for an arbitrary arrangement provided only that the geometry of the apparatus and fields remains fixed. The force equation for a charged particle in any system of fields is $\mathbf{F}=e(\mathbf{E}+\mathbf{v}\times\mathbf{H}/c)$. But

$$\mathbf{F}=m\mathbf{a}=m\frac{d\mathbf{v}}{ds}\cdot\frac{ds}{dt}=mv\frac{d\mathbf{v}}{ds},$$

where $s$ is the distance measured along the orbit and $v$ is the magnitude of the vector velocity $\mathbf{v}$. Therefore

$$\frac{mv}{e}\frac{d\mathbf{v}}{ds}=\mathbf{E}+\mathbf{v}\times\mathbf{H}/c. \qquad (9)$$

Now suppose that $\mathbf{E}$, $\mathbf{H}$, $\mathbf{v}$ and $m/e$ are multiplied by the scalar constants $\alpha$, $\beta$, $\gamma$ and $\delta$ respectively:

$$\delta\gamma^2\frac{mv}{e}\frac{d\mathbf{v}}{ds}=\alpha\mathbf{E}+\gamma\beta\mathbf{v}\times\mathbf{H}/c. \qquad (10)$$

Eq. (10) will reduce to (9) and give the same path for the new particle provided $\delta\gamma^2=\alpha=\beta\gamma$. Hence

$$\left.\begin{array}{l}\delta=\beta^2/\alpha\\ \gamma=\alpha/\beta\end{array}\right\}. \qquad (11)$$

These are the conditions for the configuration of trajectories to remain unaltered when $m/e$ is changed by the factor $\delta$ and shows that $m/e$ varies directly as $H^2$ and inversely as $E$ at the exit slit of the mass-spectrograph if the initial velocity satisfies the relation for $\gamma$.

Suppose $(m/e)_1$ and $(m/e)_2$ characterize the particles passing through any two points 1 and 2 respectively while $(m/e)_1'$ and $(m/e)_2'$ describe the particles passing through the same points after the change in the fields. Then $(m/e)_1=\beta^2/\alpha(m/e)_1'$ and $(m/e)_2=\beta^2/\alpha(m/e)_2'$, or

$$\frac{(m/e)_1}{(m/e)_2}=\frac{(m/e)_1'}{(m/e)_2'}. \qquad (12)$$

This expression of the theorem is appropriate for comparing masses that fall on different points of a detector such as the photographic plate. The proof of this theorem makes unnecessary the derivation of these properties in special cases.

# Teaching Algebraic Signs in Optics

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In general physics textbooks one is struck with the lack of uniformity and simplicity in presenting the subject of algebraic signs to be given to numerical values when substituting them in standard mirror and lens formulas. Houston's *A Treatise on Light* puts the matter as follows:

"The formulae giving the positions of the images formed by mirrors and lenses are algebraic. Thus, if $v$ denotes the distance of an image formed by a mirror from the mirror, and we solve for $v$, we may find for an answer a value such as $+10$ cm or $-7$ cm. It has hitherto been usual in elementary textbooks on light to take the direction opposed to the incident light as positive; thus $v=+10$ cm means that the image is 10 cm from the mirror on the side from which the light is coming, and $v=-7$ cm means that the image is 7 cm distant on the other side. In coordinate geometry and in plotting graphs on the other hand, positive numbers are always measured to the right and negative numbers to the left, and there is so much graph plotting done in schools now that this convention is very well understood. The two conventions agree or clash according to the side of the page from which the light comes.

"In this book we shall adopt the convention of coordinate geometry throughout, and $v=-7$ cm will denote that the image is 7 cm to the left of the mirror, no matter from which side the light comes. There is no reason why a student should unlearn his coordinate geometry when he starts to study light, since the one convention possesses no advantage over the other."

The writer has examined twelve or more standard American textbooks on general physics for colleges and finds numerous confusing rules which are rather tiresome to memorize and apply. The criticism seems to be that authors give algebraic signs to the properties of mirrors when they are really independent of any coordinate system. In teaching it really is not necessary to attach any definite algebraic sign to a concave mirror or a converging lens, or to the focal length of a diverging lens or to the radius of curvature of a convex mirror. The coordinate system chosen can take care of signs for every special case. Two typical cases of the textbook treatments are given to emphasize the need of adopting some simple standard convention of signs such as that for rectangular coordinates.

### Textbook 1

*Mirrors:* The formula $1/u+1/v=2/r$ applies both to concave and convex mirrors. The radius of curvature $r$ is positive for a concave mirror and negative for a convex mirror. The object distance $u$ is positive for a beam diverging from a real object and negative for a beam converging to a virtual object. The image distance $v$ is positive for a beam converging to a real image and negative for a beam diverging from a virtual image.

*Lenses:* The equation $1/u+1/v=1/f$ is applied to all cases of image formation by diverging, as well as by converging, lenses. The focal length is positive for converging lenses and negative for diverging lenses. The object distance is positive when rays diverge from a real object and negative when rays converge to a virtual object. The image distance $v$ is positive when rays converge to a real image and negative when rays diverge from a virtual image.

### Textbook 2

*Mirrors:* The formula $1/u+1/v=2/r=1/f$ applies both to concave and convex mirrors. Each of the distances $u, v, r, f$ is positive when it refers to points on the same side of the mirror as in the case of a concave mirror forming a real image.

*Lenses:* The formula $1/u+1/v=(n-1)(1/r_1+1/r_2)=1/f$ is used for all lenses. The rule of signs is taken from the case of a double convex lens forming a real image: $u$ and $r_2$ are to the left, while $v$ and $r_1$ are to the right of the lens. Each distance is considered positive when measured on the same side of a lens as in the foregoing standard case and negative when measured on the opposite side.

It would appear that a uniform and simple convention of signs, one that the student has already learned in mathematics, would appeal to authors of textbooks. To demonstrate its adaptability to optics, the coordinate geometry convention of signs will be considered here with the standard mirror and lens formulas,

$$\text{Mirrors:}\ \frac{1}{v}+\frac{1}{u}=\frac{2}{r}=\frac{1}{f}$$

$$\text{Lenses:}\ \frac{1}{v}-\frac{1}{u}=(n-1)\left(\frac{1}{r_1}-\frac{1}{r_2}\right)=\frac{1}{f},$$

where $u$, $v$, $f$, $r$ and $n$ stand for object distance, image distance, focal length, radius of curvature and index of refraction respectively. The rule states that *mirrors or lenses are to be considered as at the origin of coordinates so that distances to the right are positive and those to the left are negative.* Also, $r_1$ *refers to the side on which the light is incident and* $r_2$ *refers to the emergent side;* a lens can be placed in any way but the numbering must conform to the rule. No other rules are necessary. Mirrors and lenses need only be classified as *converging* and *diverging*. By this rule the focal lengths and radii of curvature take on the signs of the coordinates as the case may be. One would not speak of mirrors or lenses with positive or negative focal lengths, nor of a positive or negative lens;[1] such terms would be superfluous. Several examples will be given to show how the rule is applied.

*Mirrors*

To find the image distance when an object is 25 in. in front of a mirror with a radius of curvature of 10 in.:

(1) When the mirror is concave and faces the object to the left, $1/v+1/-25=2/-10$; hence $v=-6.25$ in., or the image is 6.25 in. to the left of the mirror.

(2) When the mirror is concave and faces the object to the right, $1/v+1/25=2/10$; hence $v=6.25$ in., or the image is 6.25 in. to the right of the mirror.

(3) When the mirror is convex and faces the object to the left, $1/v+1/-25=2/10$; hence $v=4.16$ in., or the image is 4.16 in. to the right of the mirror.

(4) When the mirror is convex and faces the object to the right, $1/v+1/25=1/-10$; hence $v=-4.16$ in., or the image is 4.16 in. to the left of the mirror.

*Lenses*

To locate the image of an object 25 in. from a lens with radii of curvature of 10 and 12 in., and index of refraction 3/2.

(1) For a converging lens (radii of curvature in opposite directions), with object to left of lens and the lens placed with the surface of greater curvature to the left, $1/v-1/-25=(3/2-1)(1/10-1/-12)$; hence $v=19.3$ in., or the image is 19.3 in. to the right of the lens.

(2) With object to right of lens, other things being the same, $1/v-1/25=(3/2-1)(1/-12-1/10)$; hence $v=-19.3$ in., or the image is 19.3 in. to the left of the lens.

(3) For a diverging lens (radii of curvature in opposite directions), with object to left of lens and the surface of greater curvature to the left, $1/v-1/-25=(3/2-1)(1/-10-1/12)$; hence $v=-7.6$ in., or the image is 7.6 in. to the left of the lens.

(4) With object to right of lens, otherwise the same, $1/v-1/25=(3/2-1)(1/12-1/-10)$; hence $v=7.6$ in., or the image is 7.6 in. to the right of the lens.

These examples are sufficient to show the workableness of this convention. The question of whether an image is real or virtual can be decided by the fact that real images are figures formed by real light from the object, whereas virtual images are only apparent figures from which the real light appears to come.

[1] The international convention of opticians agreed to call a converging lens "positive" and a diverging lens "negative." This probably has its advantage in business but it is not good when teaching theory.

The question of whether a lens is converging or diverging can be decided by the constants of the lens; namely, the relative index of refraction of the lens with respect to the surrounding medium, and the radii of curvature.

The question of the algebraic sign to use with the focal distance $f$ in any special case where none of the constants $r$, $r_1$, $r_2$, $n$ are given can be determined from the general properties of the mirror or lens, and the relation $2/r=1/f$ for mirrors and $(n-1)(1/r_1-1/r_2)=1/f$ for lenses. In the case of mirrors it is seen that $f$ takes the same sign as $r$; for converging mirrors the concave side is always toward the object and $r$ has the same sign as $u$, whereas for diverging mirrors the convex side is toward the object and $r$ has the opposite sign as $u$. In the case of lenses it is seen that $f$ takes the sign of $(1/r_1-1/r_2)$; for converging lenses this quantity always reduces to a quantity with a sign opposite to that of $u$, whereas for diverging lenses it reduces to a quantity with a sign the same as $u$.

The conclusion to the whole matter is that the properties of lenses and mirrors have to do with their constants and are determined independently of the convention of algebraic signs which may be chosen. With the properties of mirrors and lenses thus independent of the convention of algebraic signs chosen, it follows that the simplest and most sane choice of signs is to assume distances to the right of a mirror or lens as positive and those to the left as negative in harmony with what one has already learned about rectangular coordinates in mathematics, as stated in the quotation from Houston at the beginning of this paper.

The English have taken a big step in this direction. A large committee was appointed by the Physical Society of London, in April, 1929 to investigate this and other subjects in the teaching of optics in England. The committee's 86-page report[2] makes many suggestions and recommendations. In regard to algebraic signs, Chapter VI classifies the representative English books according to sign conventions used. The books are classified into three groups, with many cases in each group. This shows how much need there is for consistency and continuity in the treatment of geometrical optics. In order to unify the teaching practices in England, the report recommends the use of one of two systems; namely, one based on the rectangular coordinate system, the positive direction being the direction of the initial progress of light, or one not based on the rectangular coordinate system, but using real distances as positive and virtual distances as negative.

The writer would recommend to American teachers and authors the system based on rectangular coordinates with the signs independent of the initial progress of light as outlined in this paper. He uses it in teaching because the students already know the conventions from their study of mathematics and, because it seems more simple and fundamental.

[2] *Report on the Teaching of Geometrical Optics* (Cambridge Univ. Press, 1934). See Am. Phys. Teacher **3**, 140 (1935).

## Survey of Educational Films

A SURVEY to list all motion pictures which have an educational value is being conducted jointly by the U. S. Office of Education and the American Council on Education. This includes not only the strict classroom film, but subjects useful to scientific workers, vocational classes and other specialized educational groups. The survey is being made under a grant from the General Education Board and is being carried on by the American Council on Education in connection with its sponsorship of the proposed American Educational Film Institute. Any person or organization that has produced or has the distribution rights to any film that should be included in this list, and who has not received the film cards sent out under this survey, should write to the American Council on Education at 744 Jackson Place, Washington, D. C.

# Illustration of a Conservation Paradox

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WHEN the moment of inertia of a rotating system changes by reason of a redistribution of the mass of the system, it is often difficult to reconcile two fundamental principles of mechanics: conservation of energy and conservation of angular momentum. Obviously if the angular momentum $I\omega$ is conserved during a change of moment of inertia $I$, it is impossible for the kinetic energy of rotation $I\omega^2/2$ to be conserved; or if kinetic energy is conserved, angular momentum must change. To emphasize this dilemma the author has devised a simple apparatus to illustrate the contrast between these two conservation principles. Its operation is based upon two rather familiar problems in mechanics which give excellent examples of the distinction between the time integral and the line integral of a force.

**Ex. 1.** *A particle of mass m attached by a cord to a vertical rod moves on a smooth horizontal plane in a spiral path as the restraining cord winds itself about the rod. Given an initial speed of rotation $\omega_1$ when the length of cord is $r_1$, what angular speed will the particle have when the cord has shortened to $r_2$?*

**Ex. 2.** *The same particle is started from the same point with the same initial speed; but this time it moves along the same spiral path by reason of an external force pulling the cord through a hole coinciding with the center of the rod previously used. What will be the angular speed when the length of cord is again reduced to $r_2$?*

The initial conditions of position and speed are the same, and the final positions are the same; but the final speeds are distinctly different. One is tempted to apply the principle of conservation of angular momentum to both examples: but in the first case there is an unexpected pitfall, for here the angular momentum of the particle is partially transferred to the supporting system by reason of the torque exerted by the force in the constraining cord upon the central rod. It might be supposed that the momentum thus transferred would be insignificant and that the difference in final speeds, if any, would be trivial. But this is not true; the final linear speed in the second example is much larger than that in the first, and even larger than the initial linear speed. The difference becomes more pronounced as the ratio $r_1/r_2$ increases. Why? In the second example there is conservation of angular momentum, inasmuch as the force upon the particle acts centrally. But if angular momentum is conserved, the kinetic energy of the particle must *increase*.

An apparatus that demonstrates this paradox is shown in Fig. 1. A 1-in. ivory ball B is constrained by the cord C to roll on the horizontal glass plate G, a 30-in. plate from a discarded electrostatic machine. Ballistic impact from the iron ball A starts the ball B from its initial position which is fixed by teeing B in the hole of a thin washer cemented to the glass plate near its edge. If desired, an electromagnet may be used to retain the iron ball until the operator is ready to release it; or, more simply, the ball A may be released manually from its supporting clamp. The construction of the fixed axis and spindle is shown in the insert. The pivot P with its axial hole H is fastened to the center of the glass plate. Through this hole passes the cord that connects the ball B with the windlass W. The edges of this hole are rounded to prevent undue wear or cutting of the cord. The removable spindle S is a 0.5-in. tubular piece of brass which slips snugly over the pivot P. A narrow vertical slot T allows its placement or removal without disturbing the position of the horizontal cord attached to the ivory ball. Thus the apparatus may be quickly adapted to illustrate either case of rotation. In the first case, the spindle S is inserted; as the ball B rolls around the horizontal plate, it winds the cord about the spindle. The ball moves along an involute of the spindle, thus shortening its own

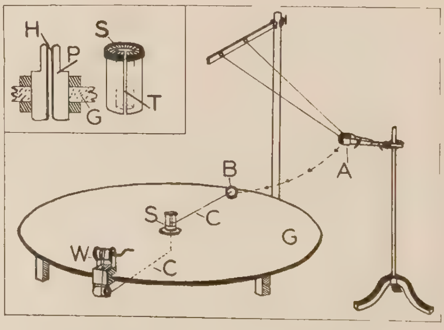


Fig. 1. Demonstration of the conservation paradox.

radius of revolution by a length equal in each revolution to the circumference of S. In the second case the spindle S is removed, the ball is given the same initial speed, and for each revolution upon the glass plate the cord C is shortened by turning one rotation on the windlass W, whose drum is equal in diameter to the spindle S. Thus it is assured that the ball will follow very closely the path described in the first example. However, the speed acquired by the ball under these latter circumstances is astonishing. It is evident that the loss of energy by friction in the two cases is practically the same since the two paths are of equal length;[1] therefore the difference in final speeds must be due to the manner in which the ball B is caused to traverse its path. The simple performance of this experiment leaves no doubt in the mind of the observer that a real difference exists at the end of two nearly similar sequences of events.

In Ex. 1 the angular momentum is conserved, *but not in the ball;* there is an unexpected transfer of momentum to the supporting system, which one is likely to overlook. The kinetic energy of the ball is conserved, except for frictional losses, and the *linear* speed remains constant while the angular speed increases inversely as the radius of rotation. It is an interesting exercise to show that the angular momentum lost by the ball is equal to the angular impulse imparted to the supporting system through the spindle. The angular impulse is equal to the torque acting upon the spindle integrated over the time required for the ball to go from $r_1$ to $r_2$. This integral is independent of the radius of the spindle S; for if S is small the torque is small but the time is long, and *vice versa*.

In Ex. 2 there is conservation of angular momentum of the ball, with a consequent *increase* of kinetic energy. The additional energy is imparted, obviously, by the external force applied to the windlass. In this case, the instantaneous radius of curvature of the path does not coincide with the direction of the cord; therefore, there is a component of the force in the cord acting along the path, whose *line integral* from $r_1$ to $r_2$ is equal to the change in kinetic energy of the ball. This is in contrast to the first case, in which the motion is always perpendicular to the constraining cord, and no change in linear speed occurs; that is, the force in the cord is a true centripetal force referred to a moving center, whose *time integral* represents the change in angular momentum of the ball.

The angular speed of the ball is inversely proportional, in the first case, to the radius; in the second case, to the *square* of the radius. The force in the cord varies inversely as the radius in the first case; it varies inversely as the *cube* of the radius in the second case. Thus, in the latter case, when $r_2$ is made small compared with $r_1$, the increase in centrifugal force may be sufficient to break a strong fishline!

[1] Loss of energy due to twisting of the cord as the ball rolls may be reduced by passing the cord through a diametral hole in the ball, or by using a swivel joint. Friction and rolling are neglected in this discussion.

## Approaching the Study of Interference Through Acoustics

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IN the study of wave propagation, two of the most fundamental subjects are those of interference and diffraction. The usual approach to these subjects in elementary courses is mainly by way of optics rather than acoustics. Few elementary textbooks do much more than point out the existence of these phenomena in acoustics. Pedagogically, however, this procedure has certain drawbacks. The beginner is handicapped at the very start in optics because he finds himself in strange territory. He meets there alleged "waves" of incredibly short wavelengths, and of enormous frequencies and speed. He must work with slits a small fraction of a millimeter wide, must learn to manipulate telescopes, adjust and calibrate micrometer eyepieces, measure exceedingly small angles. All this seems strange and bewildering to him.

It is very different, however, when the approach to these topics is through acoustics. The

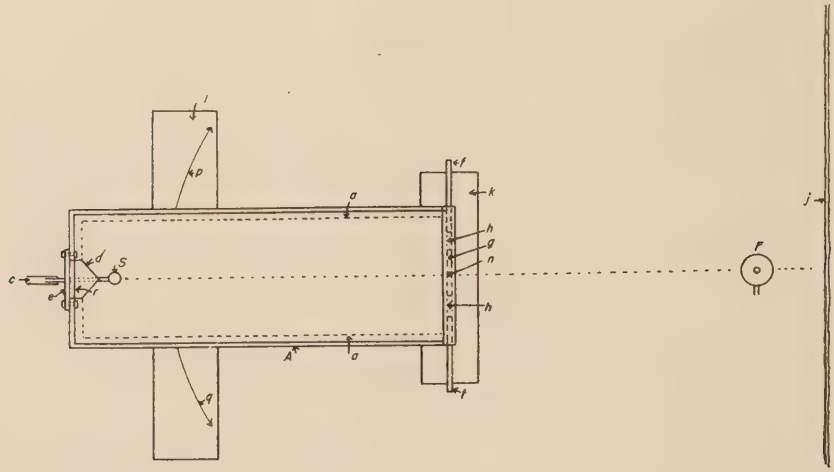

FIG. 1. Plan of sound-box.

student is at once sure he is dealing with waves. He actually can "see" them—or at least photographs of them made by the method of spark photography. He can measure their wavelengths, frequencies, and speed directly. He can play with apertures and slits of decent dimensions and can at will make them large or small as compared to wavelengths. He can with simple, inexpensive apparatus and ordinary skill study the essentials of an acoustic analogy of Young's famous experiment on a large scale and actually measure path differences directly. And, when studying interference in thin films (analogous to Newton's rings, optical interference in soap bubbles and wedges, etc.), he can determine directly the relation between wavelength and thickness of film.

That these and many other fundamental phenomena in this field lend themselves easily both to demonstration before whole classes and to individual study in the laboratory in a quantitative, or at least semiquantitative, way seems not to be as well known as it should be. Since we know of no laboratory manual outlining such experiments nor of any apparatus supply house offering equipment designed for such experimental study, it may be of interest to describe our equipment and six fundamental experiments on interference that can be performed with it.[1] No doubt more satisfactory sources and receivers can be devised, but we wish to show what can be done with a very simple and inexpensive set-up. All new parts are homemade. Everything else needed is standard and probably is available in every laboratory.

1. *Double Slit.* In Fig. 1, *A* is a wooden box, $30\times45\times120$ cm, lined inside with a thick layer of balsam wool *a* to minimize internal reflection. The sound source is a Galton whistle *S* which is actuated by compressed air, at constant pressure, admitted through tube *c*. It is mounted vertically immediately in front of a wedge *d* on a door *e* which can be removed to permit adjustment of the whistle. Single and multiple slits may be formed at the opening of the box by introducing the two doors *f* and any desired number of slats *g* between them. These slide in grooves *h*. At *F* is the receiver, a sensitive flame carefully adjusted to give maximum sensitivity for the particular pitch used. A blanket *j* is mounted behind the flame in order to prevent reflection of sound from the walls of the room.

For best results the sensitive flame should remain at rest during the exploration of the interference pattern while the sound-box is moved relative to it. The box is therefore placed upon two boards *k* and *l* on a table. In *k* at point *n* is a hole into which fits a peg projecting from the bottom of the box. The box can then be swung about *n* as a pivot, as suggested by curve *pq*. In this manner the whole pattern is rotated with respect to the flame, and the successive fringes

[1] We have also developed apparatus for the study of diffraction due to rectangular and circular openings, obstacles and zone plates, etc. These we hope to describe in a later paper.

are brought into coincidence with it. The flame is depressed for maxima of intensity and burns steadily for minima. Since it is easier to locate accurately the minima, the measurements are always made with them. The acoustical paths from the slits to the orifice of the flame are measured directly with a meter stick or tape, and the path differences for the various orders calculated simply by subtraction. No equation involving trigonometric functions is necessary. Such simplicity is, of course, impossible in optics.

One can change rapidly and at will all fundamental factors affecting the interference pattern: slit width, distance between slits, wavelength, distances from slits to receiver. To study the effect of *all* such changes quantitatively is, of course, not required of the ordinary beginner though such a study would make a valuable project for the exceptional student. It is, however, decidedly worth while for all students to investigate all such effects qualitatively and a few of them quantitatively in the lecture room and laboratory.

2. *Thin Films.* Fig. 2 shows the essential features of the film model. At $a$ is a strip of ordinary window screen (functioning as a partial reflector like a half-silvered mirror or the first reflecting surface of a soap solution film) mounted in a rectangular frame fixed on base $d$. At $m$ is a board (functioning as a mirror) mounted on a carriage $e$, the runners of which slide in grooves $c$. By moving the carriage back and forth with respect to the screen, the thickness of the "film"

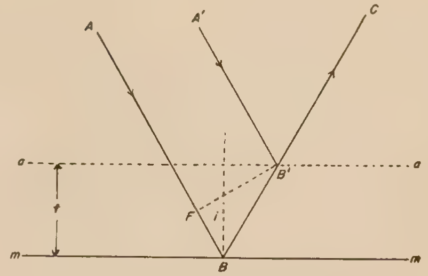


FIG. 3. Interference due to a thin "film." $FB'$ is drawn perpendicular to $AB$ and $A'B'$. There is destructive interference along $B'C$ when $BB'+BF=n\lambda/2$. But $BB'=t/\cos i$; and $BF=BB'\cos 2i=t\cos 2i/\cos i$. Hence $t(1+\cos 2i)/\cos i=n\lambda/2$, or $t=n\lambda/4\cos i$.

can be varied at will. Suppose now that this apparatus is placed in front of the open sound-box and sufficiently far from it (say several meters) so that one can consider the incident waves to be very nearly plane parallel.[2] In Fig. 3 let $AB$ be a ray incident on the mirror $mm$ and let $BC$ be the reflected ray cutting $aa$, the partial reflector, at $B'$. Let $A'B'$ be the incident ray which is reflected partially by the screen, also in the direction $B'C$. The condition for destructive interference along $B'C$ is

$$t=n\lambda/4\cos i, \tag{1}$$

where $t$ is the distance between the screen and mirror, $n$ is an odd integer, $\lambda$ is the wavelength, and $i$ is the angle of incidence. When this condition is satisfied, the sensitive flame placed anywhere along $B'C$ (but not in the direct beam from the box) burns steadily, thus indicating that no sound reaches it. By Eq. (1), the wavelength can be determined, since $t$ and $i$ can be measured directly. Furthermore, the distance between successive positions of $mm$ for which the interference is destructive is given by

$$t_n-t_{n-2}=[n\lambda-(n-2)\lambda]/4\cos i=\lambda/2\cos i, \tag{2}$$

as can easily be confirmed experimentally.

By means of screw $f$ (Fig. 2) the screen, which is hinged at the base, can be rotated about a horizontal axis. Likewise, the mirror can be rotated about the vertical axis through the pivot

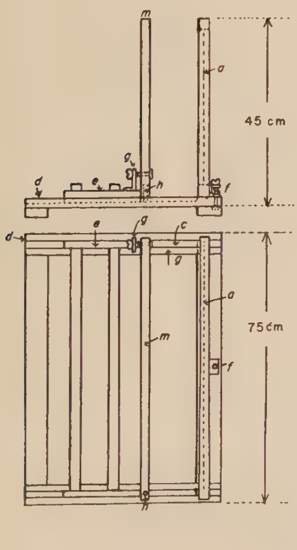


FIG. 2. Side and top views of "film" model of variable thickness.

[2] For obvious reasons it is important, too, in this and succeeding experiments, that only the central diffraction band due to the opening of the box fall upon the apparatus. This can be brought about by adjusting either the distance to the apparatus from the sound-box or the aperture of the box.

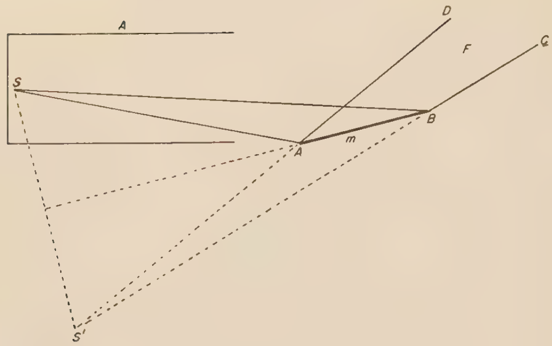


FIG. 4. Illustrating the theory of Lloyd's mirror.

$h$ by means of screw $g$. In this way wedge effects can be studied.

An obvious advantage of this experiment, pedagogically, is that the question of interference is not complicated by questions of refraction and of change of phase upon reflection as is the case in optics.

3. *Standing Waves.* The screen can easily be removed from the apparatus of Fig. 2. If the mirror and base are then set directly in front of and perpendicular to the axis of the open sound box, standing waves are produced. The sensitive flame may be set up at any point between the box and the mirror. Nodes and loops can then be produced at the flame[3] by moving the mirror back and forth in a direction parallel to the acoustic axis. It is easier to locate the nodes than the loops. Of course, when the distance between neighboring nodes is measured, it is always found to be a half wavelength.

4. *Lloyd's Mirror.* If the mirror $m$ is placed obliquely with respect to the acoustic axis, as in Fig. 4, we shall have interference in the region $ABCD$ of the intersection of the direct beam from source $S$ and the reflected beam from image $S'$. This can be demonstrated by moving the flame about within that region, provided one is fortunate enough to have a flame that can be moved without losing its sensitivity; or, if the flame must remain fixed, by rotating the mirror about a vertical axis, thus changing the distance $SS'$ and hence the conditions of interference at any given point $F$. The equations need not be discussed here.

5. *Fresnel's Mirrors.* The source is at $S$ in the sound-box $A$ (Fig. 5). The mirrors are $m_1$ and $m_2$. These produce virtual images at $I_1$ and $I_2$. Interference takes place in the shaded area. The flame is placed at a point $F$ outside of the direct beam from the box; that is, at a point where the effect of the diffraction due to the aperture of the box is negligible.

The existence of discrete interference fringes can be demonstrated either by moving the flame about within the proper area, or by rotating the whole mirror system about $i$, the intersection of the planes of the mirrors, as an axis. It can be shown that the fringe system is not distorted by such rotation. For quantitative work, the ordinary familiar equations of optics apply.

Fig. 6 shows the details of the mirror system. The mirrors $m_1$ and $m_2$ are two polished boards, each $25 \times 35$ cm. Mirror $m_1$ is fixed to the board $B$; $m_2$ is hinged to $m_1$ and is free to rotate about $i$. A peg projecting from the bottom of $B$ fits into a hole in $C$. This permits the rotation of $B$, and therefore of the mirror system, about $i$ with respect to $C$, which remains fixed on the table.

6. *Effect of Plane Reflector Near Point Source.* The sound-box of Fig. 1 is employed, except that doors $f$ and $g$ and wedge $d$ are removed,[4] and the whistle is so mounted that its distance from the

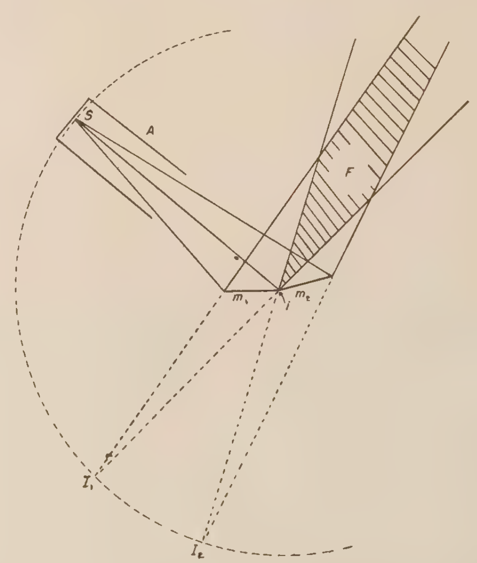


FIG. 5. Illustrating the theory of Fresnel's mirrors.

[3] That under these conditions the positions of the nodes and loops do not depend upon the distance of source to reflector, as they do, for instance, in the Kundt's tube, has been discussed recently by Pielemeier, Am. Phys. Teacher 3, 89 (1935).

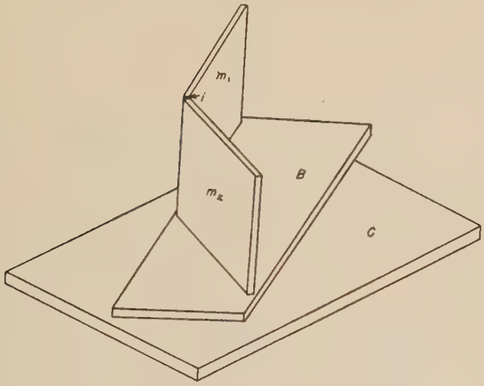


FIG. 6. Fresnel's mirrors.

plane reflecting surface $r$ can be varied at will by external control. One easily can demonstrate that there will be destructive interference everywhere along the line between[5] $S$ and $F$, through the sources perpendicular to the reflecting wall whenever the distance from $S$ to $r$ is an odd number of quarter wavelengths. This is to be expected, because in that case the reflected sound will be opposite in phase to that coming directly from the source. Naturally, it is equally possible to demonstrate constructive interference along the same line $SF$ when the distance is any number of half wavelengths.

So far as we are aware, this surprisingly simple and exceedingly instructive experiment has no direct analog in optics. Probably it would be impossible. The nearest approach to the experimental study of interference in the line joining two sources, or rather one source and its image, is by indirect methods,[6] such as by Meslin's arrangement of the split lens experiment.

The advanced student will also find it instructive to study interference in this case at points off the acoustic axis.

TABLE I. *Comparison of results.*

| EXPERIMENT | λ, cm |
|---|---|
| 1. Double slit | |
| $d=27$ cm | 2.9 |
| $d=22.5$ cm | 2.9 |
| 2. Thin film | 2.74 |
| 3. Standing waves | 2.8 |
| 5. Fresnel's mirrors | 2.88 |
| *Resonance tube* | 2.8 |

*Typical Results.* Because of lack of space detailed data will not be given. However, it is important to show that the results of the different experiments are in rather good agreement. Thus Table I shows the results obtained in about six hours by a student who worked quantitatively on Exps. 1, 2, 3, and 5. The same whistle setting and air pressure, and hence the same wavelength, were used throughout. Each figure given is the mean of repeated independent measurements. In Exp. 1, for instance, all orders of fringes were measured first for a distance between slits of 27 cm and then for a distance of 22.5 cm. As a check on these results by a method already familiar to the student, the wavelength was determined also by the standard resonance tube method.

There are many ramifications of this series of experiments which cannot be discussed here. Any teacher can think of many that would be suitable as projects and minor research problems for the more adventurous student.

These experiments have been demonstrated before members of the physics departments of the University of Nebraska, Nebraska Wesleyan University, Doane College, and the Omaha South High School. This paper has been perused in manuscript by Professor D. G. Hilts of Union College and by several members of the physics department of the University of Iowa. We are deeply grateful for criticisms and encouragement from all these sources.

[4] The purpose of the wedge in previous experiments now becomes apparent: it eliminates the effects outside of the box of a plane reflector near the source.

[5] Between $S$ and $r$ there are standing waves, as in Exp. 3.

[6] For good discussions of such experiments the student can be referred to Preston, *Theory of Light* (Macmillan, 1912), p. 168, or Wood, *Physical Optics* (Macmillan, 1921), p. 147.

## Reprints of Survey Articles for Class Use

REPRINTS of Dr. Walker Bleakney's article on "The Mass-Spectrograph and Its Uses," which appears in this issue, may be obtained for class use at cost from the Editor. The price for 6 reprints is 65 cts. postpaid.

# APPARATUS, DEMONSTRATIONS AND LABORATORY METHODS

## A Rotatable Stand and Switch for Crookes Tubes

W. F. POWERS AND G. W. ALDERMAN, *Physics Laboratory, Massachusetts State College, Amherst, Massachusetts*

THE rotatable stand with built-in switch shown in Fig. 1 enables the lecturer to demonstrate to a class the properties of cathode rays very conveniently. Suppose that he wishes to demonstrate in succession the following properties of cathode rays: (1) rectilinear propagation, (2) normal propagation from the cathode surface, (3) heating effect, (4) fluorescence, (5) deflection by magnetic field. By this device he can set the switch to operate tube (1), and then slowly rotate the top part of the stand so that a student in any part of the lecture-room can look straight at the tube. By turning the switch one notch farther, the next tube is similarly used, and so on. The stand also provides a convenient way of storing the tubes until they are to be used again. It requires only about $2 \times 2$ ft. of lecture-table space.

The stationary base of the stand is a piece of $\frac{3}{4}$-in. plywood about 18 in. square. To this is fastened a sheet-copper ring, say 10 in. in diameter and 1 in. wide. At the center of this base is attached a short metal rod to serve as axle for the rotatable platform (24 in. across) which carries the tubes. The platform bears on "domes of silence" mounted on the base. The high-voltage leads from an induction coil are brought to the copper ring and metal rod respectively. A plunger type of cupboard catch fastened to the lower face of the movable platform makes contact with the copper ring on the base. Another similar catch is mounted horizontally inside of the square wooden block at the center of the platform so that the plunger is in contact with the metal axle. The Crookes tubes are held in wooden blocks. Dowel-rods of wood, 6 in. long, are fastened to the platform, one back of each tube, and on each dowel-rod are two copper bands about 2 in. apart. Fine wires connect the electrodes of the tubes with these bands. The central wooden post with handle (selector) is provided with two short, horizontal, wooden dowels which terminate in strips of spring brass, $3 \times \frac{3}{8}$ in.; these brushes wipe over the bands just mentioned. A flexible wire goes from the cupboard-catch bearing on the copper ring up a dowel rod post set in the platform near the catch and then to the upper brush of the selector. The other lead is a flexible wire from the second catch to the lower brush of the selector. Looking down on the apparatus, all the top electrical contacts are put at ground potential. It would be a simple matter to arrange an electro-magnet to provide the field for the tube that requires it.

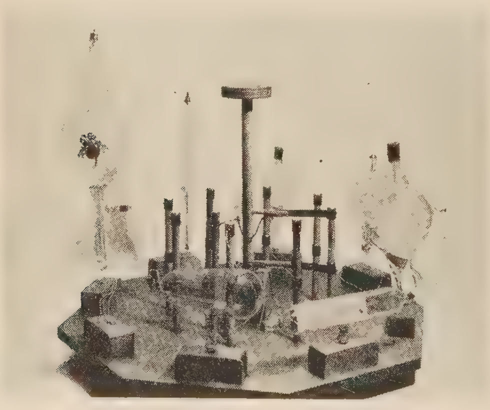

FIG. 1. Display stand for Crookes tubes.

Although considerable time is required to assemble this rotatable stand and switch, the writers are confident that it is well worth while. The lecturer can give the demonstrations in a darkened room with ease and full assurance that they will "work."

# A Projection Cloud Chamber [1]

M. Stanley Livingston, *Department of Physics, Cornell University, Ithaca, New York*

Of all the large and complicated apparatus used in studying the sub-microscopic world of the nucleus, the Wilson cloud expansion chamber is the simplest and the best for making the subject visualizable to the student. In such a chamber a supersaturated vapor condenses on ions formed in a gas by the passage of a charged particle of high speed, such as an $\alpha$-particle, a proton or an electron. This results in a "track" which can be observed under suitable illumination. Several types of cloud chambers are now available for table demonstration purposes, but it is advantageous to have an apparatus for the projection of such tracks on a lantern screen. The cloud chamber described in this note is simple enough to be built in the most modest laboratory and of such design as to allow satisfactory projection with the standard vertical projection lantern.

The chamber (Fig. 1) consists of a brass cylinder about 2.5 in. in diameter and 2 in. long, on the ends of which two circular glass plates are waxed with Dennison's red Express Sealing Wax. A tube of diameter 0.5 in. is soldered into the side of this cylinder near the bottom, and terminates in a rubber hydrometer bulb. The bulb and chamber are filled with distilled water to a level about 0.5 in. from the top. Compression and expansion of the air above the water, which forms the cloud chamber proper, is accomplished by motion of the water "piston" through alternate squeezing and relaxing of the bulb. A clearing field to draw out the surplus ions is maintained by having a thin ring of copper foil under the top glass plate connected through suitable protective resistance to a 110-volt d.c. supply. This copper ring is insulated from the brass cylinder by a ring of mica and the joint is sealed with wax on the outside as shown in Fig. 1. Brass rings of somewhat larger diameter than the chamber are placed above and below the glass plates and bolted together to prevent the compression from blowing

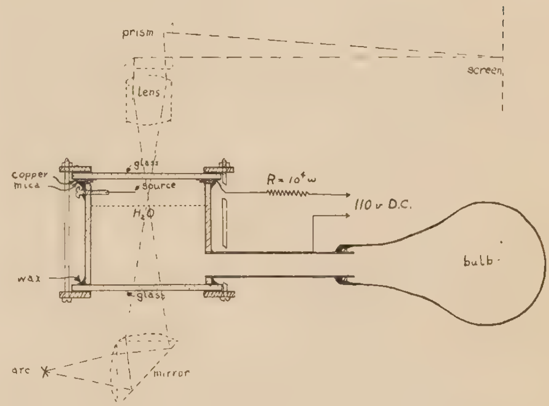


Fig. 1. Diagram of projection cloud chamber.

off the plates. The source of $\alpha$-particles in the chamber is a wire on the tip of which a minute quantity of polonium has been deposited by electrolysis from a solution of radium residues.

The projection must be accomplished with the chamber on a horizontal plane. This involves the standard type of vertical projection lantern with the light source, mirror and condensing lens below the horizontal platform and the projection lens and prism above. The chamber should be brightly illuminated and give an image about 10 ft. in diameter on the screen. The $\alpha$-particle tracks are observable immediately after expansion as black lines extending from the source; they last about 1 sec. and waver some due to the turbulence of the air in the chamber. The forked tracks occasionally observed indicate nuclear collisions with the gas or vapor in the chamber. Slight warming of the top glass plate with a flame or electric heater will prevent the accumulation of moisture on the glass. Expansions should occur at not less than 10-sec. intervals to give the best results. The expansion ratio to give the sharpest tracks may be determined by varying the degree of compression of the bulb or by changing the level of the water in the chamber. The ratio between volumes at expansion and compression should be about 1.25.

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[1] This apparatus was first developed by Dr. Franz N. D. Kurie at the University of California.

## A Simple Demonstration of an Analogy to the Electromotive Force, Potential Difference and Resistances in a Circuit

LEONARD B. LOEB AND H. M. HERREMAN, *Department of Physics, University of California, Berkeley, California*

THE use of the hydrodynamic analogy in the presentation of current electricity has proven quite useful in the experience of one of the writers and he has long wished to be able to illustrate it to a large class. This has been precluded in part by the lack of satisfactory pumps of small capacity and convenient size such that the whole circuit could be assembled in a small compass on the lecture table. The appearance on the market of "Fountainette," a telechron motor-driven circulating pump of low price,[1] gave us the opportunity to develop the apparatus quite conveniently.

The device, shown in Fig. 1, consists of a shallow trough $T$, at least 20 in. square and 6 in. deep, the front side facing the class being of glass. In it, on a convenient wooden base, is the intake $I$ of the small rotary pump $P$. The telechron motor $M$ is protected from dripping water by the small copper hood $H$. The large vertical glass cylinder $C$ is closed at its lower end by a two-holed rubber stopper and is supported by a clamp immediately above the motor. This cylinder should be 40–50 in. high and about 2 in. in diameter. Rubber bands $B$ are provided to mark the levels of the water under the various conditions. Connected to two tubes coming from the stopper at the base of $C$ are two glass manifolds, $MO$ and $MI$. The one, $MI$, has at its lower end two tubes, $RI1$, and $RI2$, each about 8 in. long and having an inner diameter of 3/16 and 1/16 in. respectively. One or the other of these tubes is to be connected in turn to the pump by very short straight rubber tubing of large bore, the other being closed with a rubber stopper. These two tubes, $RI1$ and $RI2$, are to be used to illustrate the effect of changing the *internal resistance* of a source of potential. The second manifold $MO$ has five tubes descending from it. These tubes are provided with stoppers and are arranged so as to discharge into the tank $T$ or into graduate cylinders standing in $T$ if so desired. Each tube is 8 in. long, except $RO3$ which is 16 in. long. $RO1$ has an inner diameter of 3/16 in.; $RO2$, 1/8 in.; the others, 1/16 in. They represent *external resistances*. The connections of the manifolds to $C$ should be as short and wide as possible.

A suggested series of operations is as follows. Let $RI1$ be placed in the circuit, all other outlets being closed. On starting the motor, the water will rise to $B_1$, about 20–24 in. above the stopper in $C$; this represents the *electromotive force* because the height is determined only by motor speed and pump characteristics. If then $RO3$, corresponding to a high external resistance, be opened, the level will fall an inch or two to $B_2$; this represents the potential maintained with a small current running. On opening $RO4$ and closing $RO3$, the fall will be to $B_3$, about twice that for $RO3$. If $RO4$ and $RO5$ are open, one has two equal resistances in parallel, and the fall to $B_4$ will be nearly double that due to $RO4$. Closing $RO4$ and $RO5$ and opening $RO1$ represents practically a dead short

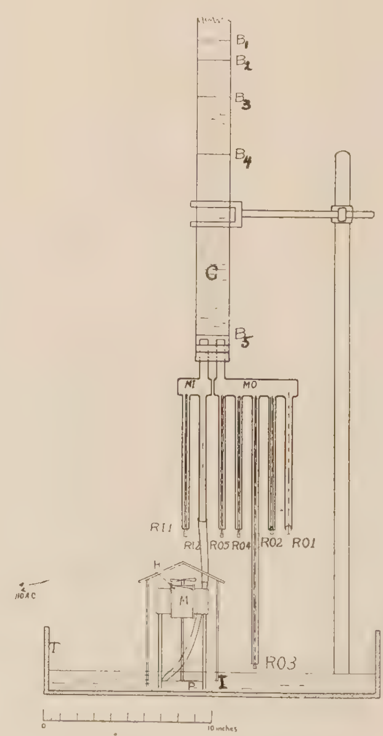


FIG. 1. Water analogy of an electric circuit.

[1] C. W. Marwedel & Co., 71 First Street, San Francisco; price \$4.00 to \$9.00, dependent on size. In this work "Fountainette" pump No. 2A was used.

circuit and the level falls to $B_5$, that of the cork. The internal resistance $RI1$ can then be replaced by $RI2$ and the slow rise in $C$ on open circuit, and the correspondingly large changes in the level of the water in $C$ for the same series of external resistances, $RO3$, $RO4$ and $RO5$, can be noted. The apparatus is so flexible that many modifications may be introduced to illustrate additional properties of a circuit, such as measuring the currents by graduated cylinders, thus exhibiting the apparent failure of Ohm's law observed when the internal resistance is appreciable and the change in potential is not corrected for, etc. The apparatus may also be used in laboratory instruction, by paralleling measurements with it by the equivalent electrical measurements.

## Surface Tension Apparatus, Photometer, and Torque Board Design

C. J. Overbeck, *Department of Physics, Northwestern University, Evanston, Illinois*

The apparatus of any student laboratory is a silent but forceful teacher. Its design, in physics especially, plays a considerable part in helping the student to learn what the laboratory aims to teach him. In an introductory course the prime requisites for the apparatus are simplicity, ruggedness, and a fair degree of accuracy of results. The three pieces of apparatus described possess these features and also can be constructed easily and at small cost. They are in use in our freshman laboratory.

### Surface Tension Apparatus

In the direct measurement of the surface tension of liquids the force required to draw a horizontal wire from the liquid surface is measured. Good results can be obtained only if this wire is of small diameter and of considerable length. Commonly the wire frame is made either too heavy for accuracy or else too delicate for the beginner to use. To gain the stability necessary for repeated handling by first year students without sacrificing accuracy, a frame $F$ (Fig. 1) was made of nickel wire of 0.76 mm diameter, and a fine tungsten wire $T$ of 0.12 mm diameter, used for the measurement, was spot-welded across its face. This frame is attached to the Jolly balance[1] shown schematically in Fig. 1 and is slowly drawn from the liquid by raising $R$. The screw $S$ is used to raise the mirror $M$ so as to keep the spring hook and its image always on the hair line of the mirror as the frame lifts from the liquid. The scale reading at $P$ is made when the film breaks. Then the spring frame $R$ is lowered for the same mirror cross-hair setting of the spring hook, without the film, and a second reading made. The difference between the two readings gives accurately the spring elongation due to the film. The student then calibrates the spring, using known masses, and measures the length of the tungsten wire for comp ete data.

[1] Described in Am. Phys. Teacher **3**, 34 (1935).

### Photometer

Measurements of the luminous efficiencies (candle power per watt consumed) of a carbon filament and a Mazda lamp, for various terminal voltages, are made the connecting experiment between the subjects of electricity and light. It was desired to have for this a photometer box which could be used without darkening the room, so that other experiments might be run at the same time. Such a box to be satisfactory should permit a large shift of the lamps and still not be too cumbersome to store.

Fig. 2a shows the top view of the box. The cover is removable so that the student may change the test lamps as well as examine the inside of the box. The lamps used in the box are attached to their sliding bases $B$ by means of heavy brass rods extending through slits $C$. Observation is made through the demountable sighting tube $T$ (Fig. 2b). The comparison screen is at $S$; it is circular, 2 cm in diameter, and is viewed in the mirror $M$ (Fig. 2c). The standard lamp and the lamp to be tested are

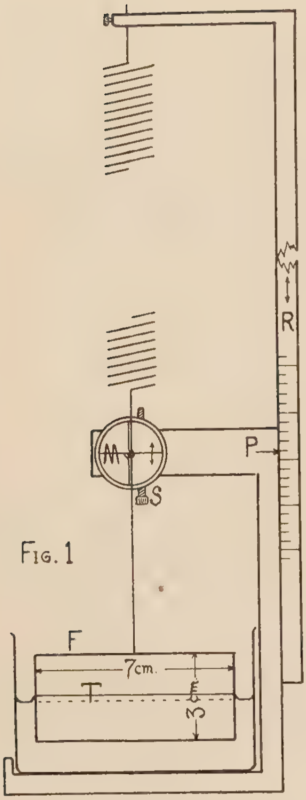


Fig. 2a

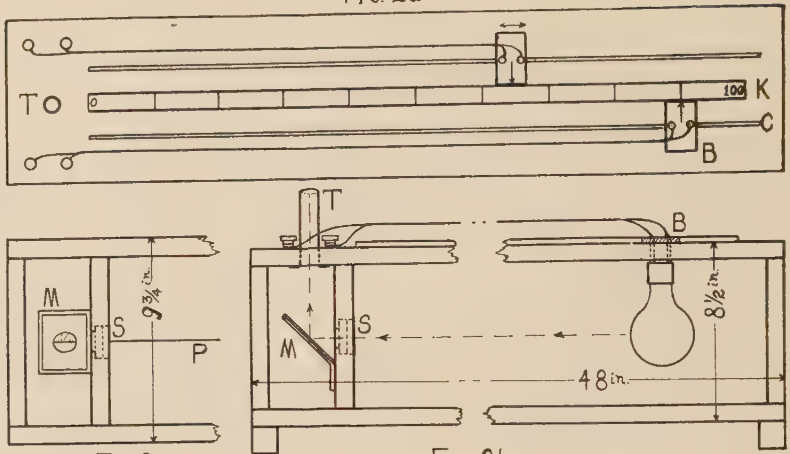


Fig. 2c

Fig. 2b

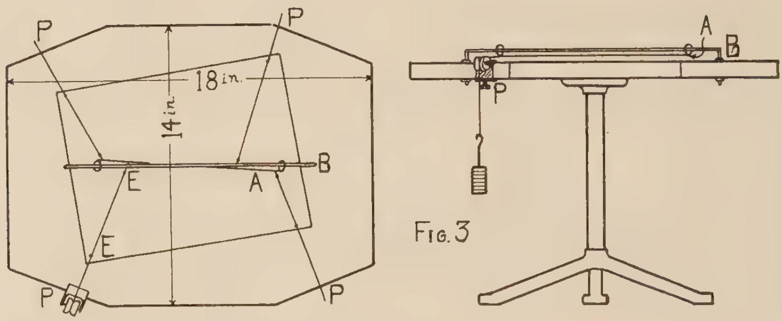


Fig. 3

Fig. 1. Diagram of surface tension apparatus.
Fig. 2. Diagram of photometer, showing (*a*) top view, (*b*) side view of interior, (*c*) top view of screen and mirror.
Fig. 3. Top and side views of torque board.

separated by a black sheet-metal partition *P*. In making a reading the lamps are moved back and forth along the meter stick *K* until the two halves of the screen *S* are equally illuminated as seen in the mirror. Since tests are run on different lamps operated at different voltages the color trouble tends to make comparison difficult. This is practically avoided by placing glass Corning Filters Nos. 349 and 430 over the fine tracing paper of the screen. These filters permit a comparison of a quite narrow band of light with its maximum at approximately 5700A and give results that are in fair agreement with those obtained with a flicker photometer.

## Torque Board

In order to impress the student with the fact that the direction of a force as well as its magnitude must be considered, which is frequently forgotten in the usual "Parallel Forces Experiment," the apparatus shown in Fig. 3 is being used. This "torque board" consists of a light brass rod *A* with four cords passing over the force table pulleys *P*. The cords are loaded so that the rod clears its rings from the check rod *B*. Rod *B* is fastened to a $3/4 \times 14 \times 18$-in. plywood board cut as shown and attached to a force table tripod. After obtaining an equilibrium condition the student slips a sheet of paper under the cords and locates the position of points *E* under each cord. These points, with a record of the loads on each cord, suffice to show that there is a balance of forces (graphically) and a balance of torques (mathematically). The apparatus has been found very instructive and allows an accuracy of results that satisfies the students.

## A Novel Method of Measuring the Coefficient of Dynamic Friction

V. E. Eaton, *Scott Laboratory, Wesleyan University, Middletown, Connecticut*

A SATISFACTORY experiment for the elementary laboratory should arouse the interest of the student, give reasonably accurate results, and require the application of fundamental physical laws. The method of determining the coefficient of friction $\mu$ between dry solid surfaces described here, has been in use for the last three years and apparently is superior to the older methods in all of these respects.

The apparatus for determining $\mu$ for various substances on oak is illustrated in Fig. 1. The plane $P$ was made of well seasoned oak, sanded to an accurately plane surface by rubbing it on a large sheet of sand paper clamped to a plane surface, and then rubbed smooth with another piece of wood. The upper end of this plane is provided with a combination release latch and switch. With the lever $L$ in its upper position the latch $J$ fits into the latch-way $W$ and the block $B$ containing the test material is held in position. Depressing $L$ releases the block and simultaneously closes the switch $S_1$. When the block reaches the foot of the incline it automatically opens the switch $S_2$ and falls into a box $R$, heavily padded and lined with canvas. The switches are held in either the open or closed positions by spring-actuated V-shaped plungers (Fig. 1). Since the primary of the door-bell transformer $T$ is connected to the 60-cycle lighting circuit while the secondary, the Cenco impulse-counter $I$ (No. F787), and the switches $S_1$ and $S_2$ are connected in series, the counter

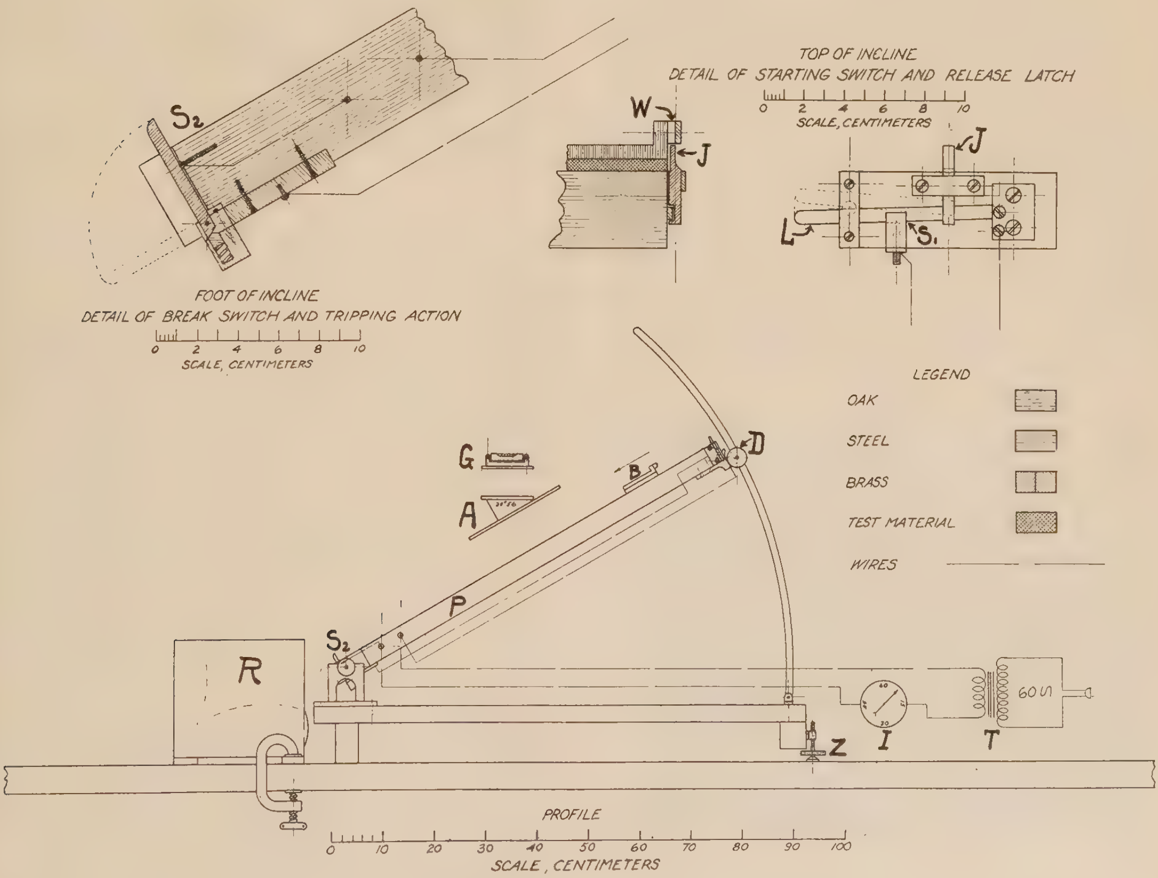


Fig. 1. Inclined plane for dynamic friction.

indicates the time of descent in 120ths of a second. Somewhat better results can be obtained if the secondary of the transformer, the counter, and a variable resistance are connected in series, the resistance adjusted so that the armature of the counter vibrates slightly but not sufficiently to register, and the switches $S_1$ and $S_2$ used to short out this resistance. The frequency meter at the power station indicates that in the territory covered by the New England Power Association it is unusual for the frequency to depart more than 0.1-cycle from the 60-cycle value and that during the afternoon the departure is even less.

At $A$ is shown one of five standard angles for each of which the angle has been carefully determined and marked on it. With a No. 96 Starrett sensitive level $G$ on its upper surface, $A$ is held on the plane and the plane adjusted so that $G$ is level. The angle $\theta$ that the plane makes with the horizontal is then the angle marked on $A$. The angle is adjusted approximately with the clamp $D$ and finally, with the levelling screw $Z$. An alternative method of determining $\theta$ is by the use of a No. 364C Starrett vernier protractor ($V$, Fig. 2) with a sensitive level mounted on one arm.

Fig. 2 shows a similar piece of apparatus with a 1/4-in. steel plane reinforced with 1.5-in. steel angles. Various materials, e.g. linoleum, may be clamped on this plane. Fig. 2 also shows the method used to investigate the constancy of the acceleration of the block and to check the

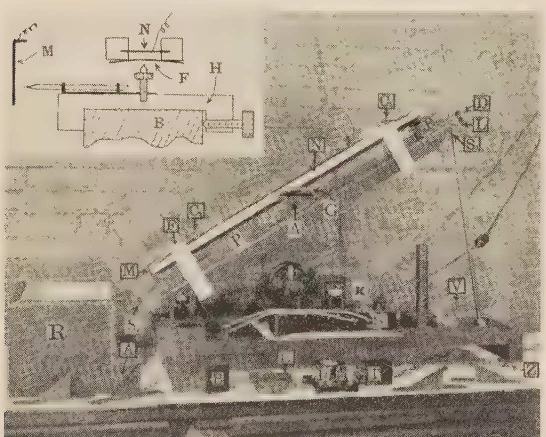


Fig. 2. Steel plane equipped for spark recording. Inset: cross-section of spark recording device.

results obtained with the counter. $K$ is a No. F1178 Cenco-Behr timing device, giving 30 sparks/sec. $S_1$ and $S_2$ take the place of the regular spark switch $S_3$ on this apparatus. The Formica yoke $H$ with two adjustable points is clamped on the block $B$. When $L$ is depressed and the block released, sparks at the rate of 30 per sec. pass from the side electrode $M$ to $H$ and from $H$ through the sensitive paper $F$ (Cenco No. F1180A) to the electrode $N$. $F$ is held in place by paper clips $C_1$ and $C_2$ and tension is provided by rubber elastic attached to $C_2$.

In taking data for Table I, $\theta$ was adjusted to correspond to the largest of the five calibrated angles and five different determinations of the time of descent $t$ were made in the manner indicated. Similar data were taken for the other angles in order of decreasing angles. A spark record was then made, after which another series of impulse-counter readings was taken, this time in order of increasing angles. In this manner, if $\mu$ varied, it could be ascertained whether the variations were due to differences in velocity or to a progressive change in the character of the surfaces.

When the impulse counter was used, the value of $\mu$ was determined from the equation

$$\mu = \tan\theta - \left(\frac{2S}{gt^2 \cos\theta}\right). \qquad (1)$$

The strip of paper $F$ was removed from the frame and the position of each (or each odd) spark puncture recorded. The difference between consecutive readings divided by the time interval was taken as the velocity at the midpoint of the time interval. The velocities as a function of elapsed time (measured from the first spark) are plotted in Fig. 3. Similarily, the average acceleration is computed by dividing the velocity intervals by the corresponding time intervals. The value of $\mu$ (bottom row, Table I) is computed from the average acceleration thus determined.

Since it is departure from linearity that is significant, all the lines in Fig. 3, except $F$, are drawn straight. Evidently the assumption in deriving Eq. (1), that the laws for constant acceleration can be applied, is justified except in the case of $F$ and possibly $D$. This conclusion

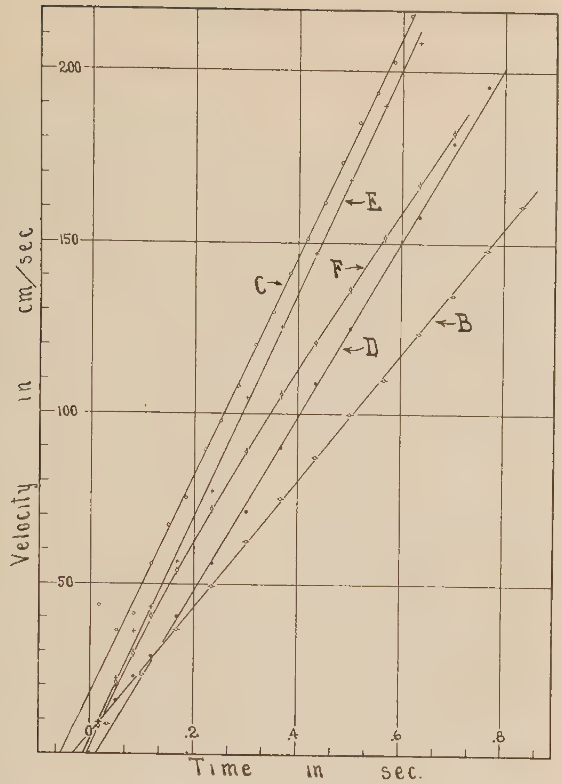


FIG. 3. Velocity *vs.* time, computed from spark records. Letters have same significance as in Table I. For $B$, $\theta=24°\ 58'$; for $D$, $\theta=20°\ 2'$; for remainder, $\theta=29°\ 56'$.

is further justified by the work of Jenkin and Ewing.[1] It is also seen that, with the exception of these two materials, the values of $\mu$ for the various angles and for the two methods are in excellent agreement with one another and with the values recorded in handbooks. However, since $\mu$ depends to such a marked extent upon the condition of the surfaces, including humidity, tables are almost useless. All that can be said with confidence is that between two certain samples on a certain day $\mu$ had a particular value.

The spark record for $B$, Table I, was made 6 days after the data for the other values of $\mu$ in this column were taken. In the meantime the value of $\mu$, measured by taking 10 values of $t$ for $\theta=29°\ 56'$, had increased to 0.247. The actual value, from the spark record, was 0.251 and the

TABLE I. *Coefficients of friction of various materials on a plane making an angle $\theta$ with the horizontal.**

| Materials / Angle $\theta$ | $A$ | $B$ | $C$ | $D$ | $E$ | $F$ |
|---|---|---|---|---|---|---|
| 39° 58′ | .235 | .223 | .227 | .056 | .203 | .244 |
| 35° 03′ | .245 | .223 | .228 | .068 | .201 | .255 |
| 29° 56′ | .244 | .224 | .228 | .065 | .203 | .256 |
| 24° 58′ | .242 | .223 | | .071 | .199 | .250 |
| 20° 02′ | .246 | .224 | | .074 | .201 | .248 |
| Spark | | .228** | .230 | .093 | .200 | .276 |

* $A$, oak on oak, motion parallel to the grain; $B$, oak on oak, motion perpendicular to grain on block; $C$, shoe leather on waxed linoleum; $D$, bronze (flat surface) on steel; $E$, bronze (surface grooved parallel to direction of motion) on steel; $F$, leather on steel. In the bottom row each value of $\mu$ is computed from a single spark record with the plane set at the angle indicated in the legend of Fig. 3.
** Corrected value.

corrected value 0.228. Values for $C$ for smaller angles could not be obtained since the static friction was too large to permit the block to start. Students like to work with these materials because of the obvious practical significance. The extremely small value of $\mu$ for $D$ is due to the fact that with the velocities used here the bronze block rides on a cushion of air and that above 30 cm/sec (see Fig. 3) it is mainly air friction that is being measured. This effect was minimized in $E$ by grooving the surface of the bronze block. The surface of contact between block and plane consisted of 16 ridges 1 mm wide, separated by grooves 3 mm wide and 2 mm deep. In this case the latchway $W$ should be considerably wider than the latch $J$ in order that the ridges will not invariably trace the same path at the upper end of the plane, causing progressive changes in $\mu$ at this end which are not duplicated at the lower end. Since in the case of $F$ the value of $\mu$ is decidedly a function of the velocity (see Fig. 3), the counter method is unsatisfactory. The spark method can be used successfully but it should always be stated for what velocity the value of $\mu$ applies. To minimize progressive changes in $\mu$, the leather surface was thoroughly washed and rubbed down with a cloth while still wet, thus giving it an unusually smooth surface. For this reason the values of $\mu$ for $F$ are all considerably less than the values found in tables.

Progressive changes in $\mu$ were not serious, amounting to an over-all change of 0.013, or less, in all cases except $F$, where the change was 0.027. When making five determinations of the time of descent for a particular angle the maximum variation of any single observation from the mean value of $t$ was in almost all cases less than 2 percent and in most cases was about 1 percent. Both surfaces were wiped with clean paper after each observation to remove all lint and dust. In the case of wood surfaces, if the block is too heavy, the character of the surfaces may be changed by the heat developed. If the block is too light an air cushion may develop between the surfaces as in $D$. The 7×7-cm block used here weighed 500 g and proved to be quite satisfactory.

[1] Phil. Trans. Roy. Soc. **167**, 509 (1877).

## Lantern Demonstration of the Triple-Point for Water

W. F. POWERS, *Department of Physics, Massachusetts State College, Amherst, Massachusetts*

A DEMONSTRATION of the triple-point of water which is roughly quantitative may be shown readily to a large class by using an apparatus designed for lantern projection and a thermocouple with lecture-room galvanometer for temperature indication. With the apparatus to be described, usually not more than two or three minutes are required for the whole demonstration.

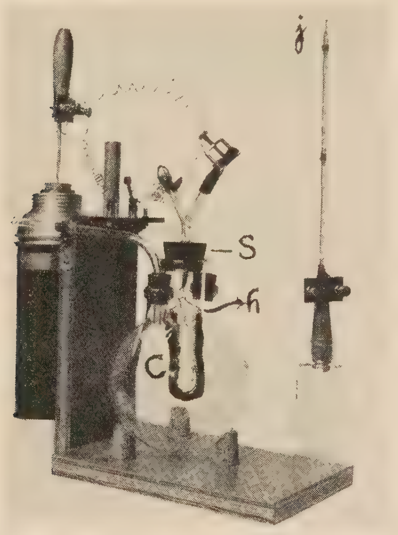


FIG. 1. Photograph of apparatus.

A 1-l flask with three necks (Fig. 1) is mounted on an L-shaped wooden frame so that it can be placed on the lantern bed. Short bends of glass tubing from the smaller necks are fastened to the sides of the wooden upright and afford separate connections to a pump and a gauge. The cell *C*, which carries both the water "to be boiled and frozen at the same time" and a copper-constantan thermo-junction, must be thin to make lantern projection successful. It is made from two microscope slides laid on a U-shaped bend of glass tubing (5 mm outside diameter), the outer edges being made water-tight with sealing-wax. If the upper ends *h* of the glass U are formed into little inverted hooks, the cell can be supported by fine wire from the large stopper *S* in the middle neck of the flask. The thermocouple wires are brought out through the left branch of the glass Y-tube, the outer end of this branch being made air-tight by wax. To the top of the wooden upright is attached a piece of bakelite which contains two binding posts and a small single-pole switch for short-circuiting the galvanometer. On the side of the upright remote from the flask is attached a pint-size thermos-bottle containing melting ice in which is placed the second thermo-junction.[1] A little calcium chloride is dropped into the flask, and then the cell is filled to a depth of 2–3 cm with cool, distilled water.

With the apparatus in adjustment, the class can observe the decrease in galvanometer deflection with decrease in pressure until the formation of ice is observed on the lantern screen. The galvanometer is now short-circuited, and the class sees that the temperature of the cell is practically zero. If a large dial vacuum gauge is used the class can see that the pressure also is about zero. If desired, the cell containing the ice may be removed easily and passed around for individual inspection. Obviously the whole apparatus can be made much smaller.

It is the writer's experience that this method of demonstrating the triple-point is more interesting and instructive to the students than the bell-jar method.

[1] This thermo-junction, also shown supported by a bottle at the right in Fig. 1, is useful for other demonstration experiments. A small wooden file handle holds two pieces of 1-mm glass tubing about 20 cm long through which copper and constantan wires pass from the soldered junction *j* to binding posts at the other end. Two such assemblies, with color-coded connecting wires, and a thermos-bottle for the fixed temperature are often useful.

# DISCUSSION AND CORRESPONDENCE

## Problems of a Survey Course for Teachers College Students

VARIOUS phases of the college survey courses in the natural sciences have been discussed in some detail in previous issues of this journal.[1] Having been associated with a survey course in physical science for several years, I believe that some further discussion of this type of work may be of value. May I say at the outset that, as a teacher of physics, I entered upon the survey course with considerable misgivings as to its value and possibilities. In common with most physicists, I have been accustomed to departmentalized science and consequently have always felt that, for instance, a chemist was best fitted to teach chemistry. However, the fact remained that most of our students finished a general college course with only a semester or two of science, often biological, taken to fulfill curriculum requirements. Yet these same students completed several English, history and social science courses on the assumption that such studies were necessary for a professional and cultural education. The question we faced was, whether a familiarity with Shakespeare was more desirable for such an education than an elementary knowledge of the solar system or of "talking movies."

If one is prepared to agree that some acquaintance with physical science should be a part of the equipment of every college graduate, the question arises as to what type of course is best for the purpose. During the time that we have been experimenting with the survey course—and the word "experiment" is used advisedly—certain fundamental problems have become evident.

Among the students in the average freshman class there are some who have been interested in science in the secondary school, but there are many who are convinced that physical science is a bugbear. Although students have had the same variety of interest in other subjects, such as English, most college authorities have been of the opinion that all freshmen should pursue certain fundamental English courses no matter what their previous interest may have been. A logical conclusion would be that certain science courses should be given to all freshmen. Up to the present there seems to be no one course in the regularly organized physical science departments that serves the purpose. It is evident that if the survey course is to fulfill the requirements, it must be so planned that all students will profit.

Another vital problem is the teacher. Shall the course be offered in units as at the University of Chicago, a few weeks in the geology department, a few weeks in the physics department? Or shall one teacher conduct the entire course? This is a difficult problem. I have yet to find a teacher who, when called upon to conduct survey courses, has at the outset the same enthusiasm for all phases of the subject. This is not surprising, inasmuch as the college scientist has of necessity specialized in one field and has covered the others in a cursory manner. Some might say, by all means departmentalize the survey course. The difficulty with this plan is that a physicist does not like to teach four weeks of physics, nor does a geologist like four weeks of geology. Each will exclaim "I cannot do justice to myself and the students in four weeks of three hours each"; if asked how much time is needed, such teachers probably will say that a year course is not too much. It is true that under this method the student studies with specialists in the various fields. However, it must not be forgotten that many students either through lack of interest or lack of aptitude are not adaptable to the usual first year course in a particular field of science unless there is a lowering of the college standard. Science departments should not be asked to make such a concession and, personally, I would not wish to require students to struggle through courses in which they are not interested. The departmentalized method has a further disadvantage in that there is not much opportunity for unification. There are various topics common to physics and chemistry, to physics and astronomy, and to chemistry and geology that a unified course can utilize to the best advantage. We have found that enthusiastic teachers who are willing to profit by experience can satisfactorily conduct the entire course. Survey courses are really beneficial to teachers in that they acquire a breadth of vision in science which is desirable.

Another difficult problem is the selection of material. At the outset, we decided to discuss phases of science that were believed to be closest to the experience of the average student. Such topics as the weather, stars, clothing, lenses, minerals, refrigerators and electrical appliances seemed suitable. We planned the work with the expectation that the students had carried over from their secondary school science courses a good deal of information on such subjects and decided that our aim would be to develop scientific thinking concerning these everyday experiences. To our surprise, there was little accurate information retained on any of the ordinary topics. It seems that it is a common practice of many of the smaller high schools to assign general science teaching to teachers who have not specialized in the field. In addition, there is usually a dearth of laboratory materials in such schools. A survey in New Jersey by Reed[2] showed that although physics constituted nearly one-half of the content of the average general science textbook, the average general science teacher did not have an equivalent physics training; in many cases he had less than a year of college physics. One supervisory official of the Pennsylvania State Education Department expressed the opinion that general science teaching was the poorest in the high school curriculum. In view of these facts, we found it necessary to revise our methods of presentation so that more factual material would be

included. In this connection I wish to question Dr. Havighurst's statement that survey courses may in the future be relegated to the secondary school. I do not feel that high school students have the mental age to profit greatly by a course of the survey type.

What form shall the presentation take? There seems to be a tendency in the colleges to increase the number of appreciation courses. We have appreciation of music and of art; we have civilization and culture courses. Some educators feel that a survey course in science should be an appreciation course. I am strongly opposed to such a trend. Science has had a logical development and although logical learning processes are not the path of least resistance in education, I feel that a college course in science, no matter what its character, must involve some accurate thinking on the part of the student. Moreover, if it is to be worthwhile, it also should be somewhat informative in character; I do not feel that too much of the philosophy of science can be well assimilated by the average college freshman. The methods and materials that we have found most useful are biographies, field trips, experimental demonstrations, illustrations from everyday experiences, newspaper articles, motion pictures, slides and reports of reference reading.

The problem of whether the student should do experimental work in the laboratory has required considerable thought. At the outset, it was decided that it would be desirable to have the student actually work in the laboratory at scheduled periods. Experiments on such topics as electrical circuits in the home, weather maps, camera lenses, textile study, humidity, the photoelectric cell and time zones, were carefully planned and included at the ends of the chapters of our then mimeographed text. As far as possible we attempted to prevent duplication with the work carried on in the other science courses. It was our aim to make the experiments practical and interesting. At the present time the laboratory work is still in a state of flux, but we feel that individual experimentation is very valuable to the survey student.

A further goal toward which we are striving is to give the prospective secondary school teacher of general science more training in experimental technic. Our practice teachers tell us that the student needs more opportunity to learn methods of experimental demonstration in his science sources. We believe that a survey course could help to fill this need. Unfortunately, such training requires individual attention on the part of the instructor and with large freshman classes this is impossible unless assistants can be trained to help with the work. We are hoping that the details can be arranged to provide for such assistance.

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[1] R. J. Havighurst, Am. Phys. Teacher **3**, 97 (1935); S. R. Powers, Am. Phys. Teacher **3**, 191 (1935).

[2] Rufus Reed, J. Chem. Ed., Feb., 1932.

## Reducing Grades to a Common Standard

PROFESSOR BEARDSLEY[1] seems to have devised a procedure which is practically that which a statistician probably would use were he to adjust the grades in question to a common base. The statistician would use a straight line rather than Professor Beardsley's broken line, and might use a slide rule instead of a graph. Otherwise there seems to be no essential difference.[2] However, the writer has tried various ways of averaging grades, and has finally reached the conclusion that the random fluctuations of the individual student is greater, in general, than the fluctuations due to other causes. Consequently it is usually a waste of time to endeavor to eliminate the latter. In no case in which the writer has calculated the probable error of the student's average grade has there been a significant difference between the average obtained from reduced grades and that from raw grades.

The use of the average grade and the standard deviation of a class in determining the literal grade of students is advisable only in large classes. Several years ago the writer examined the grades of approximately 2000 students of elementary physics in this college. The classes are limited to 20 students. By using the grades received in one semester from various instructors to determine the average grade of a class in another semester it was found that variations in the average of a class of half a letter from the mean occurred fairly frequently.

In the search for a better method of grading the writer developed a procedure for determining the "most likely" grade of a student based upon the idea of the median rather than the most probable value. (The *median* is the value that is as likely to be exceeded as not, whereas the *most probable value* is the value that occurs most frequently.) Thus, to take an absurd but striking case, if a single question is asked and the question is answered correctly the student is as likely as not to know 70.7 percent of the subject matter tested by the question; an incorrect answer corresponds to a knowledge of 29.3 percent of the subject. However, the procedure became complicated as the number of questions increased, and also the median value approached the most probable value. Hence the writer still uses the arithmetic mean in determining the average grade of a student.

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[1] "A Practical Method for Reducing Grades to a Common Standard," Am. Phys. Teacher **3**, 137 (1935).

[2] For details see, for example, H. E. Garrett, *Statistics in Psychology and Education* (Longmans, Green, 1926), p. 281 *et seq.*; C. V. L. Charlier, *Die Grundzüge der Mathematischen Statistik* (Verlag Scientia, Lund, 1920), p. 62.

### Some Laboratory and Demonstration Aids

*1.* DR. WOOD cemented plate glass on ground glass surfaces with Canada balsam thus eliminating the time and difficulty ordinarily required for fine polishing the rough surfaces. The writer has used this scheme for overcoming the surface irregularities of pressed glass prisms of the cheap crown glass variety. A large prism of this type with faces $5\times 10$ cm was thus converted into a useful instrument by cementing plate glass on two of its faces. The total cost of the completed prism was about $1.75.

*2.* Florence flasks and spherical distilling bulbs filled with distilled water are useful for condenser systems in optical work. A 500-ml flask is the only condenser used in the writer's arrangement of the Millikan oil-drop experiment and with a 400-watt projection lamp as the source of light, gives a good field in a 64-power telemicroscope. A bulb 1 cm in diameter blown on the end of a small glass tube, filled with water and sealed, furnishes fair interference figures when conical illumination is necessary for the microscopical study of crystals under polarized light.

*3.* For making tracings on glass, as in the case of the vibrograph and falling-body apparatus, apply a thin film of any light oil to the glass and then, with the glass held in an almost vertical position, pour talcum powder along its surface. This gives a surface that offers the minimum of friction to the tracing point.

*4.* A vivid illustration of the molecular motion of gases is presented by a loosely covered glass jar on the bottom of which are small bits of cork or pith about 1 mm in diameter, enough to make a depth of 0.5 cm. A glass tube extending through the top to the bottom of the jar serves to admit a blast of air. The rapid motion of the particles caused by the air currents is greatly enhanced by the magnified image when the apparatus is projected on a lantern screen.

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### The Mechanics of a Flexible Rope

PROFESSOR W. W. Sleator[1] has proposed the following problem: "Uniform and flexible rope of mass 2 lb./ft. is drawn from a stationary coil by a man who walks at the rate of 5 ft./sec. directly away from the coil over a smooth and level floor. He thus drags after him an increasing length of rope. What horizontal force must the man exert on account of the inertia of the rope?" This problem attracted much interest at Berkeley and a number of solutions were suggested by various members of the staff. The following remarks include an arbitrary selection, on the part of the writer, of a portion of these suggestions.

The simplest solution is obtained by applying the impulse equation. In order that there shall arise no uncertainty as to whether mass or velocity (or both) is changed, or as to the velocity of the center of mass of that part of the rope in motion, let us consider a specific rope of length 10 ft. and hence mass 20 lbs.

At the instant one starts to exert a force on one end of the rope, sufficient to give it a velocity of 5 ft./sec., there is zero momentum. At the instant that all of the rope has been first set in motion the momentum is $Mv=20\times 5=100$ units. The applied force has acted for 2 sec., and has moved through a distance of 10 ft., in order to accomplish this. Therefore, by Newton's Second Law, $Ft=\Delta(Mv)$, $F\times 2=100$, and $F=50$ poundals. This is the correct answer to the problem.

On the other hand, if we apply the work equation, then as Professor Sleator notes, we obtain at first sight a result only one-half as large. Thus since a mass of 20 lbs. has been given a velocity of 5 ft./sec., there has been created 250 ft.·poundals of kinetic energy. In the 2 sec. required to accomplish this, the applied force has moved 10 ft. Hence the force required is apparently 25 poundals. Since, however, we know that 50 poundals is the correct result, it follows that one-half the true amount of work done must have gone into forms of energy other than kinetic energy associated with forward motion of the rope as a whole.

It is possible to show, in any special case, that half of the energy does go into other forms, but before giving illustrations of this, let us consider the generalized work equation. This may be derived as follows.

$$F=\frac{d}{dt}(mv)=m\frac{dv}{dt}+v\frac{dm}{dt}\cdot$$

Multiply by $ds$.

$$F\cdot ds=m\frac{dv}{dt}ds+v\frac{dm}{dt}ds,$$

$$F\cdot ds=m\cdot dv\frac{ds}{dt}+dm\cdot v\frac{ds}{dt},\quad\text{and}\quad \frac{ds}{dt}=v.$$

Therefore

$$F\cdot ds=m\cdot v\cdot dv+dm\cdot v^2,$$

$$\int_{s_0}^{s}F\cdot ds=\int_{v_0}^{v}d(\tfrac{1}{2}mv^2)+\int_{m_0}^{m}dm\cdot v^2,$$

$$\int_{s_0}^{s}F\cdot ds=[\tfrac{1}{2}mv^2-\tfrac{1}{2}mv_0^2]+\int_{m_0}^{m}v^2dm.$$

This shows that the work done goes not only into the change of kinetic energy associated with change of velocity, but also into $\int v^2dm$.

In the problem given, the velocity $v$ is constant between two instants of time; hence $v=v_0$ and

$$\int_{s_0}^{s}F\cdot ds=\int_{m_0}^{m}v^2dm.$$

Also $dm=ds\cdot\rho$, where $\rho$ is the mass per unit length; therefore

$$Fs=\int_0^s v^2\rho ds=v^2\rho\int_0^s ds=v^2\rho s,$$

or $F=v^2\rho$. Here $v=5$ ft./sec., $\rho=2$ lb./ft. Therefore $F=50$ poundals.

In conclusion consider two special cases, one applying to a perfectly elastic structure and the other to a perfectly inelastic structure.

(*a*) Assume that the rope consists of a linear series of

mass points (particles) connected by weightless springs (attractive forces). If any mass point is displaced in the direction of the rope, it will vibrate with S.H.M. Now consider a velocity of 5 ft./sec. suddenly imparted to one end of one of the springs by means of an applied force $F$. If now we take this point of application as the origin of our coordinate system, then *relative* to this origin, the connected mass point has at this instant a backward velocity of just 5 ft./sec. As a result of this, the mass point moves away from the origin, stretching the spring. S.H.M. is thus set up, and the energy of such motion—in general partly kinetic and partly potential—is constant and equal to the maximum kinetic energy, which in this case is $mv^2/2$, where $m$ is the mass of the mass point and $v$ is 5 ft./sec. If the springs are perfectly elastic, such vibratory motion will last forever. Hence finally there will be associated with each mass point a kinetic energy of $mv^2/2$ due to the *general* forward motion of the rope, and an *equal* amount of energy of vibration *within* the rope itself. If the springs are damped, this latter energy will be transformed gradually into heat.

($b$) Consider that the rope consists of a series of links (of a chain), originally packed as closely as possible. When one end of the rope is set into motion the first link moves forward a certain distance and then suddenly "picks up" the next link. This in turn moves forward with the first link until a third is suddenly picked up, etc. We assume a perfectly *inelastic* collision at the instant each link is picked up.

To find the heat generated at each collision we proceed as follows. Let $m$ denote the mass of rope already in motion with velocity $v$ equal to 5 ft./sec. Let $dm$ (infinitesimal) represent the mass of each "link." Then the momentum *before* the collision is $mv$, and *after* the collision is $(m+dm)(v-dv)$. Hence, applying conservation of momentum, we get

$$dv=\frac{dm}{m}v. \tag{1}$$

To find the heat loss we apply conservation of energy; that is, kinetic energy before the collision equals kinetic energy *after* the collision *plus* heat generated by the collision, or $\frac{1}{2}mv^2=\frac{1}{2}(m+dm)(v-dv)^2+\text{Heat}$. Therefore, with the usual neglect of infinitesimals of higher order,

$$\text{Heat}=mv\cdot dv-\tfrac{1}{2}dm\cdot v^2 \tag{2}$$

or, using Eq. (1),

$$\text{Heat}=dm\cdot v^2-\tfrac{1}{2}dm\cdot v^2=\tfrac{1}{2}dm\cdot v^2. \tag{3}$$

Then, before the next collision takes place, the kinetic energy must be increased sufficiently to change the velocity of the moving system from $(v-dv)$ to its original value $v$. The amount of work needed is $\frac{1}{2}mv^2-\frac{1}{2}m(v-dv)^2=mv\cdot dv$, where $m$ has been used in place of $(m+dm)$, the actual mass now moving. But $mv\cdot dv=v^2dm$, by Eq. (1), and this is just twice the energy lost at the collision. In other words, between each collision work equal to $v^2\cdot dm$ is done. All of this goes momentarily into increased kinetic energy. But at the next collision half of this gain in energy goes into heat, and the other half remains as kinetic energy of the rope. Therefore the total work done is again divided into two equal parts, and one part is wasted as heat.

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[1] Am. Phys. Teacher **3**, 85 (1935).

## Recent Publications

**Aristotle, Galileo, and the Leaning Tower of Pisa.** LANE COOPER, Professor of the English Language and Literature, Cornell University. 102 p., 3 figs., 15×22 cm. *Cornell Univ. Press*, $1.50.

Professor Cooper reviews the documentary evidence bearing on the "common belief in America that Galileo, having ascended the leaning tower at Pisa, by a single dramatic experiment refuted an assertion of Aristotle that had not been challenged since the days of ancient Greece, nor then." His conclusions are quite devastating to the tradition, in the form in which that tradition is stated in the opening sentence of his book, from which the foregoing quotation is made. The study is definitely a scholarly contribution to the history of science which merits cordial acknowledgment. Physics accordingly makes its bow to a sister discipline for having prosecuted a painstaking investigation in a field which is more nearly allied to its own than to that of the investigator.

The principal conclusions which Professor Cooper draws from his study may be summarized as follows:

1. Aristotle never made the assertions which Galileo attributes to him.

2. The common belief that Galileo utilized the tower of Pisa as the scene of a public refutation of the assertions erroneously imputed to Aristotle lacks authenticity; for ($a$) Galileo, in all his extant writings, never once mentions the leaning tower and never talks of experimenting from it, ($b$) there is nothing in the writings of Galileo's contemporaries at Pisa to suggest that he ever publicly performed the experiment with which he is credited, and there are some things to indicate that he did not.

3. The discovery which Galileo is reputed to have demonstrated from the leaning tower had been anticipated and experimentally verified, and had gone on record repeatedly prior to the time of Galileo.

All this is somewhat unpalatable medicine to those of us who have for years been using the Pisa episode as supposedly authentic illustrative material in the course of our teaching. But unless some other doctor can demonstrate that the patient doesn't need the medicine, we shall have

to swallow it with such grace as we can muster. Doctor Cooper's study of the case has been sufficiently thorough to create a considerable presumption that his prescription is correct.

Fortunately for the peace of mind of those who like to center even their scientific convictions in heroic characters, Galileo's preeminence in the field of physical science possesses a broad foundation. Even in the restricted field of kinematics, his positive experimental establishment of the nature of uniformly accelerated motion far outshines the negative demonstration which he apparently did not make, at least in public, on the tower of Pisa. This part of his work is described with sufficient circumstantiality in his own writings to free us of any apprehension lest it follow the tower episode.

It is, in fact, against the background of the sheer magnitude of the man as evinced in his fully authenticated publications that the reviewer finds the principal basis for such exceptions as may be taken to Professor Cooper's treatment of Galileo. It is to be presumed that Professor Cooper would concur in the volume of scholarly opinion among historians, philosophers and men of science on the value of the work of Galileo taken as a whole. Conceding that an evaluation of the whole work of Galileo is not the theme of the book under review, it still seems appropriate to suggest that it should have been allowed to influence the attitude of the author. Statements that certain writings "cannot evince unbiased experiment" (p. 55) and that an historical character "betrays animus" (p. 43) or "betrays . . . the influence of" previous writers (p. 55) are to be interpreted quite differently in the case of a man of outstanding accomplishments than in the case of a mere plagiarist. The reviewer has been unable to discover any respect in which Professor Cooper's treatment would not have been applicable if Galileo had been in the latter class instead of the former.

Apparently proceeding from a similar spirit is the author's objection to a reference to the interval of time from Aristotle to Galileo as two thousand years, because, forsooth, it was only 1913 years (p. 18, footnote); similarly the remark that "no tower is mentioned" (p. 52) in connection with a reference by one of Galileo's interlocutors to a height of one hundred cubits—which, incidentally, is as close to the height of the tower of Pisa as can reasonably be approximated in as indeterminate a unit as the cubit (p. 51, footnote); also the enclosure of the terms 'physicist' (p. 17) and 'scientists' (p. 17) in quotation marks because the presumably representative individuals of those groups whom Professor Cooper approached did not have the information which he apparently felt they should have; and finally, the imputed self-contradiction involved in each of two illustrations of the supposed Pisa episode (p. 19; p. 20, footnote). The only term that can possibly describe such references is "carping." This is an element to be regretted in a work so obviously a result of scholarly research.

It is customary to make certain presumptive concessions to men of signal achievement, which might not be made to those of lesser caliber. One cannot help wondering whether the major experiments which Galileo did authentically perform, as one of the pioneers in that method of acquiring knowledge, may not entitle to some credence his direct statements and clear implications that he performed certain others, the details of which are not clearly specified and which are not adequately documented. Certainly, there is necessity for some qualification of the author's argument that, because Galileo misquoted Aristotle, "the likelihood that actual experiment is referred to is on a par with the sheer invention by Galileo of an utterance for Aristotle" (p. 52). The principle, "falsus in uno, falsus in omnibus," may be a useful bludgeon in legal practice, but in history and science we consider ourselves somewhat more discriminating.

Moreover, the author's principal contention is that Galileo did not conduct his experiment in the sensational and public manner with which he has so widely and apparently so erroneously been credited. Though he would probably also contend that neither did Galileo conduct at the tower any private experiments on falling bodies (pp. 30–33), the evidence on this point is very much less convincing than that on the commonly alleged public demonstration. In view of Galileo's scientific philosophy (vide, inter alia, E. A. Burtt, *Metaphysical Foundations of Physics*, Chap. III, Sec. B.), as well as of his actual record as an experimenter, it is almost inconceivable that, living near such a tower and having an absorbing interest in the motion of falling bodies, he should not avail himself, at least informally and in private, of any opportunity to use the obvious means of solving some of his problems. It is even more likely that he would have done it if he had read of the somewhat inadequate experiments previously performed, notably that of Stevinus, as the author hints was rather more than possible.

The author's citation of repeated references to a tower (pp. 45–50; p. 55, footnote) in Galileo's works forms a strange basis for his conclusion that Galileo did not have "any nameable tower or height in mind." It is worthy of note in this connection that Cajori [Science **52**, 409 (1920)] has expressed an opinion that two references in Galileo's works lend support to the thesis that he experimented from the tower of Pisa. The paucity of such references may not be as significant as critics of Galileo intimate, when it is recalled that his works were proscribed and that all of them that we now have are survivals of this process of suppression.

The removal of the accretions of myth that inevitably grow around historical figures is a laudable and necessary form of critical work. That men engaged in such criticism should express irritation at those who are responsible for the creation and propagation of the myths is understandable; but allowing such irritation to obstruct the main thesis and even transferring it to the central character is likely to defeat the very purpose of the critic.

L. W. Taylor

## First Year Textbooks and Manuals

**An Introduction to Physical Science.** Carl W. Miller, Associate Professor of Physics in Brown University. Ed. 2. 409 p., 186 fig., 9 pl., 14×22 cm. *Wiley*, $3. In this edition of a book that first appeared about four years ago, the sections on the new physics are brought up-to-date and other improvements have been made. The book is well written and, considering its length and grade, the treatment of both classical and new physics is unusually comprehensive. For example, 8 of the 39 chapters deal with: absolute temperature and entropy; electric potential; x-rays and positive rays; restricted relativity; quantum theory; the nucleus; wave mechanics; cosmic rays. Trigonometry is not used but simple quantitative methods receive considerable emphasis, especially in the problems.

**Practical Physics for Agriculturists.** Russel D. Miller, Department of Physics, Iowa State College of Agriculture and Mechanic Arts. 145 p., 70 fig., 21×27 cm. *Burgess* (Minneapolis), mimeographed, $2.25. Two-thirds of this book is devoted to heat, the remainder to electricity. The treatment is mainly descriptive and many of the problems are qualitative. Emphasis is given to simple but interesting and often novel applications of physics to agriculture.

## Intermediate Textbooks and References

**A Second Course in General College Physics.** P. L. Bayley, Associate Professor of Physics, and C. C. Bidwell, Professor of Physics, Lehigh University. 195 p., 208 fig., 21×27 cm. *Edwards Bros.*, lithoprinted, $2.50. A logical, concise treatment of fundamental physics, intended for engineering students and science majors who have had a good first year course. Calculus methods are used freely but the material is so arranged that it can be studied concurrently with beginning calculus. Copies for inspection may be obtained from the authors.

**The Fundamentals of Radio.** R. R. Ramsey, Professor of Physics, Indiana University. Ed. 2. 426 p., 430 fig., 15×23 cm. *Ramsey Pub. Co.* (Bloomington, Ind.), $3.50. A completely revised and enlarged edition of a college text and reference book on the theory and practice of radio. A list of 400 questions and problems has been added. An elementary knowledge of electricity is assumed; calculus is used in a few places. Physics as a profession obviously would profit greatly if more attention were given by physicists to the production and improvement of books like this on the applied aspects of the field, and if more courses of this type were encouraged in physics department for the many students who have interests along these lines.

**Introduction to Physical Optics.** John Kellock Robertson, Queen's University, Canada. Ed. 2. 471 p., 223 fig., 7 pl., 15×22 cm. *Van Nostrand*, $4. Good books of intermediate grade on physical optics are scarce and the present one has been used widely since its first appearance some six years ago. The new edition continues the aim of providing a comprehensive and unified introduction to the subject, with emphasis on quantitative methods. A number of sections have been revised or enlarged, some of the diagrams have been improved and a supplementary list of 53 problems has been added. Calculus is not used.

**A Textbook of Light.** L. R. Middleton, Physics Master, Latymer Upper School, Hammersmith, England. 288 p., 189 fig., 14×21 cm. *Bell* (London), 6 s. A conventional, systematic and rather concise treatment, with the last fourth devoted mainly to classical physical optics. Calculus is not used. Part of the problems are qualitative. The illustrations are confined to line drawings.

**Electrons (+ and −), Protons, Photons, Neutrons and Cosmic Rays.** Robert Andrews Millikan, Director of the Norman Bridge Laboratory of Physics, California Institute of Technology. 492 p., 98 fig., 14 tables, 13×19 cm. *Univ. of Chicago Press*, $3.50. The author's *The Electron*, which has come to be something of a classic as a reference of the source type for undergraduates, is here presented in its third revision with 6 entirely new chapters on the advances since 1924 and with many new illustrations. As in the original edition, the mathematical proofs have been put in the appendix.

## Textbooks and References for Upper Division and Graduate Courses

**X-Rays in Theory and Experiment.** Arthur H. Compton, Professor of Physics, and Samuel K. Allison, Associate Professor of Physics, University of Chicago. 828 p., 279 fig., 124 tables, 16×23 cm. *Van Nostrand*, $7.50. A modern and comprehensive treatment, already to be regarded as a standard work of reference in this field which has contributed most to our knowledge of atomic structure. The diagrams are unusually effective.

**Elementary Quantum Mechanics.** R. W. Gurney, Research Associate in the University of Bristol. 160 p., 67 fig., 14×22 cm. *Cambridge Univ. Press*, $2.35. The elements of quantum mechanics are here presented as far as possible by graphical methods, with the object of helping the experimentalist to think in terms of this theory as easily as he could formerly in terms of atomic models. As the author points out, such an approach through energy graphs not only has pedagogic advantages but is a characteristic method of attacking quantum-mechanical problems, due to the fact that the potential energy of a system, as a function of the coordinates, occurs in every form of the Schrödinger wave equation; indeed the drawing of an energy diagram often is the first step taken in investigating a given molecular or atomic problem. The mathematical developments in the book contain all the steps and include frequent references to the physical meanings and magnitudes of the quantities involved. Special attention is given to the formation of molecules. Two chapters deal with the development and application of Dirac perturbation theory.

**The Nucleus of the Atom and Its Structure.** Sigma Xi Symposium, Ohio State University, 1935. 105 p., 35 fig.

and pl., 12 tables, $17 \times 25$ cm. *Ohio Journal of Science*, paper, $1. This report should be of great interest and value to many physics students as well as to the general scientific reader. The lectures are of the survey type and are on: Nuclear phenomena and cosmic rays, by W. F. G. Swann; Energies and products involved in nuclear disintegration and synthesis, by M. L. Pool; Deuterium as a research tool in the physical and biological sciences, by Herrick L. Johnston; Artificial radioactivity, by E. O. Lawrence; and Nuclear transformations and the origin of the chemical elements, by G. Gamow. There is a Foreword by F. C. Blake. Copies may be obtained from the physics department, Ohio State University, Columbus.

## Histories and Biographies

**A Source Book in Physics.** William Francis Magie, Professor of Physics, Emeritus, Princeton University. 620 p., 111 fig., $15 \times 23$ cm. *McGraw-Hill*, $5.00. In accordance with the general plan of this series of "Source Books in the History of Science," the present volume contains excerpts, all in English, from important papers and treatises of about 100 contributors to physics from Galileo to 1898. The excerpts are prefaced by short biographical notes on the authors. Because of the immensity of the literature, Professor Magie found it necessary to limit his selections to experimental results and to such parts of theoretical results as were given in words by their discoverers. Selections from the vast amount of experiment were determined by considering what would be of interest to a student whose knowledge of physics had been acquired from textbooks. This whole series of source books is a laudable undertaking and the present volume, with its well-chosen excerpts and no obvious omissions, is a contribution of great importance to the literature of physics teaching. It should be in every college and secondary school library.

**Anecdotal History of the Science of Sound.** Dayton Clarence Miller, Professor of Physics, Case School of Applied Science. 114 p., 7 fig., 15 pl., $15 \times 22$ cm. *Macmillan*, $2.50. This is an account of the principal events in the progress of acoustics from Pythagoras to the beginning of the 20th century. It is valuable as a student reference, as a source of interesting lecture material and as a contribution to the historical literature both because most histories of science contain little or no material on acoustics and because Professor Miller doubtless is better equipped than any living physicist to write an anecdotal history in this field. He knew Koenig and Rayleigh and of course Wallace Sabine, A. G. Webster and G. W. Stewart, the three Americans who along with himself were most intimately connected with developments in sound before the World War. It is interesting to recall with the author that the present relatively great activity in acoustics began with the War and that the Acoustical Society of America, which now has some 750 members and publishes its own journal, is only seven years old.

**The Rise of Modern Physics.** Henry Crew, Professor Emeritus of Physics in Northwestern University. Ed. 2. 434 p., 17 fig., 16 portraits, $13 \times 19$ cm. *Williams & Wilkins*, $4. Three new chapters and improved illustrations appear in this edition of a deservedly popular history which has been out of print for several years. A fourth of the book deals with pre-Galilean times; the remainder with the periods up to 1905. There is an excellent chapter on the origin of electrical units. This book has the great merit of being elementary without being uncritical. It is the best of its sort so far published in English.

**Albert Einstein, A Picture of His Life and His Conception of the World.** D. Reichinstein. Tr. from the 1932 Gr. ed. by M. Juers and D. Sigmund. 255 p., 10 pl., $16 \times 23$ cm. *Stella Pub. House* (Prague), 12 s. An indifferent account.

## Miscellaneous

**Science and the Human Temperament.** Erwin Schrödinger. Tr. by James Murphy and W. H. Johnston. 192 p., 13 fig., $14 \times 21$ cm. *Norton*, $2.50. Interesting essays, essentially positivistic in their outlook, on: Science, art and play; The law of chance; Indeterminism in physics; Is science a fashion of the times?; Physical science and the temper of the age; What is a law of nature? Conceptual models in physics; and The fundamental idea of wave mechanics. The last essay is the author's Nobel Address. The book is for laymen and is not intended as an original contribution to philosophic thought.

**New Pathways in Science.** Sir Arthur Eddington, Plumian Professor of Astronomy and Experimental Philosophy in the University of Cambridge. 333 p., 4 pl., $15 \times 22$ cm. *Macmillan*, $3. The book is based on the Messenger Lectures delivered at Cornell University in 1934. The author gives his conceptions of the philosophical outlook of modern science, then discusses the consequences of the statistical type of law, and follows with four chapters on astrophysics and one on the theory of groups. He also discusses briefly the views of some of his critics. In the epilog religion receives some attention. Although one may question the value of some of Eddington's contributions to metaphysics and other fields outside of physical science, there is no doubt about his mastery of literary style; competent critics have placed him in the first rank of contemporary English stylists.

**Students' Guide to Efficient Study.** Luella Cole and Jessie Mary Ferguson. 38 p., 3 fig., $15 \times 23$ cm. *Farrar & Rinehart*, paper, 35 cts. From their investigation of the study habits of college students, the authors have formulated some helpful practical advice for the student who realizes that he does not know how to study but is willing to learn. Brief sections are devoted to planning of work, learning to concentrate, reading, reviews and examinations, memorizing, etc.

# Proceedings of the American Association of Physics Teachers

## The St. Louis Meeting, December 29, 1935—January 1, 1936

The fifth annual meeting of the American Association of Physics Teachers was held at Washington University on December 29 to January 1. The presiding officers were D. L. Webster, President of the Association, and F. K. Richtmyer, Vice-President.

Three sessions were devoted to contributed papers.

At a joint symposium with the American Physical Society the following invited papers were heard:

**The New Physics and the Undergraduate.** A. A. Knowlton, *Reed College.*

**Photoconductivity in Crystals.** A. L. Hughes, *Washington University.*

**The Copper-Copper Oxide Barrier Layer.** L. O. Grondahl, *Union Switch and Signal Company.*

The Association also joined with Section B of the American Association for the Advancement of Science and the American Physical Society in a session devoted to the following addresses:

**The Diffraction Grating.** H. G. Gale, *University of Chicago.*

**Recent Developments in Cosmic Rays.** A. H. Compton, *University of Chicago.*

**Optical and Physical Defects of High Explosives.** R. W. Wood, *Johns Hopkins University.*

At the dinner held jointly with the American Physical Society at the Gatesworth Hotel, R. W. Wood presided. President Webster was one of the after-dinner speakers.

### Meetings of the Executive Committee

The executive committee held four meetings. Members present were D. L. Webster, F. K. Richtmyer, Paul E. Klopsteg, Wm. S. Webb, H. L. Dodge, O. T. Koppius, H. B. Lemon and Frederic Palmer, Jr. Others present by invitation of the committee were Duane Roller and Henry A. Barton.

Our meeting was devoted to a general consideration of the work and present status of the various standing committees of the Association. This meeting was attended by T. D. Cope, C. J. Lapp, W. H. Michener and J. Rud Nielsen, chairmen of four of the committees. The reports presented by the various committees will appear in the journal. The rule was adopted that all standing committees be appointed for periods of two years. The President was authorized to appoint committees to study the training of physicists for industry, to cooperate with the committee of the American Films Institute, and to study the question of having the Association sponsor examinations at the senior college level for students who wish to qualify as physicists.

It was voted that the Association join with the other member societies of the American Institute of Physics in the plan for a two-day general meeting probably to be held in New York next fall for the purpose of stimulating the application of physics to industry.

The Secretary was instructed to bring before the membership the question of modifying the constitution so as to make the Editor of *The American Physics Teacher* a member ex-officio of the executive committee. Duane Roller was appointed Editor for a second period of three years. Upon his recommendation, H. W. Farwell, Columbia University, George R. Harrison, Massachusetts Institute of Technology, and E. F. Lindquist, University of Iowa, were appointed associate editors for periods of three years.

O. T. Koppius was approved as representative of the Kentucky chapter on the executive committee. H. L. Dodge was nominated to represent the Association on the governing board of the American Institute of Physics for a second period of three years.

It was voted that the dues for ordinary members remain at $3.00 for 1936 but that the treasurer be authorized to accept as annual dues, $7.50 from *Contributors* and $15.00 from *Sustainers.* It is contemplated that in the printed membership roll, to be published soon, a member who voluntarily accepts the status of contributor or sustainer will be designated as such.

### The Annual Business Meeting

The annual business meeting was held at 11:30 A.M., December 31. About 140 members were present. The minutes of the business meeting of 1934 and the report of the treasurer for the present year were read and approved. The results of the election of officers for 1936 were announced as follows:

*President*......D. L. Webster, *Stanford University*
*Vice-President*..F. K. Richtmyer, *Cornell University*
*Secretary*.......William S. Webb, *University of Kentucky*
*Treasurer*......Paul E. Klopsteg, *Central Scientific Company*

*Members of the Executive Committee:*

S. R. Williams, *Amherst College*
L. W. Taylor, *Oberlin College.*

At the request of the President, reports were made by Richard M. Sutton on the progress of the Manual of Demonstration Experiments, and by T. D. Cope, on the work of the Committee on Recognition of Teaching and Outstanding Contributions to Teaching. President Webster reported various actions taken by the executive committee in its meetings.

The Association voted an expression of its appreciation to Professor Hughes and other members of the physics staff of Washington University for the many courtesies extended. A vote of thanks was also tendered the American Physical Society for its aid and cooperation in making possible the meetings of the two societies without conflict.

William S. Webb, *Secretary*

## Contributed Papers and Abstracts

Abstracts are omitted in the cases of papers scheduled for early publication in the journal and papers read by title.

**1. An Experiment to Demonstrate a Paradox of Rotation.** Richard M. Sutton, *Haverford College.*

**2. A Simple Apparatus for Demonstrating the Effect of the Lack of Dynamical Balance of a Rotating Body.** Lester I. Bockstahler, *Northwestern University.*

**3. Automobile Brakes and the Physics of Skidding.** Elmer Hutchisson, *University of Pittsburgh.*

**4. An Experiment on Variable Linear Flow of Heat.** T. P. Long and H. Dunholter, *University of Cincinnati.*—A laboratory experiment for the advanced heat course is described in which theoretical values of temperature along a bar, obtained from a Fourier equation for variable heat flow, were compared with experimental values. One end of a 7-ft. iron bar was maintained at a constant temperature of 100°C by a steam bath. The temperature along the axis of the bar was measured at 17 points by means of thermocouples and a wall galvanometer. Data were collected over a period of 6 hr., at the end of which time the steady state practically had been reached. The experimental and theoretical values agreed to within 3.5 percent for the greatest difference and had a considerably better average agreement. The theory involved is an excellent example of Fourier analysis and its agreement with experiment is sufficiently close to give the student a feeling of confidence in it. The apparatus is to be found in almost any laboratory.

**5. Determination of Velocity of Sound by the Fizeau Toothed Wheel Method.** Harold K. Schilling, *Union College.*

**6. Experiments in Wave Motion and Sound.** V. E. Eaton, *Wesleyan University.*—(1) The inertia of a standard telephone harmonic ringer was altered to give the vibrator a resonant frequency of 60 cycles/sec. This vibrator, connected to a.c., is used to set up standing waves in a string. An aluminum disk with a pair of holes on opposite ends of a diameter was geared to a synchronous motor, the gear ratio being 59/60; with a 250-watt lamp behind the disk, this serves as a stroboscope to study the standing waves in the string. (2) Minor improvements in the design of a Kundt's tube have been made. With this tube, designed for use with various gases, one or two strokes of the rod are sufficient to produce the dust patterns. (3) An electrically driven horn for the study of architectural acoustics by the Sabine method is described. The frequency, intensity, and distribution of sound in the room have been studied and found satisfactory. (4) Apparatus is described for measuring the surface tension of transparent liquids from the velocity of capillary waves. The liquid is placed in a flat bottomed glass dish. A wire frame carrying a.c. and passing between the poles of a pair of permanent horseshoe magnets dips into the liquid and generates waves having the same frequency as the a.c. Below the dish is a special lamp having a straight horizontal filament and above it is a translucent screen. Each wave acts as a cylindrical lens and forms an image of the filament on the screen. The light from the lamp is interrupted by a disk on the shaft of a synchronous motor thus causing these images to remain stationary. The wave-length of the ripples, computed from the average distance between the images, is multiplied by the frequency to obtain the velocity; the surface tension is computed from the wave equation. Five determinations of the surface tension of water gave an average value of 72.92 dynes/cm at 20°C, with a maximum deviation of 0.26 percent from the mean. This deviation is somewhat less than the error introduced by a departure of 0.1 cycle from the assumed value of 60 cycles. Excellent agreement was also obtained for organic liquids. For salt solutions the values were, as anticipated, somewhat higher than those given by static methods.

**7. A Mechanical Vibrator for Demonstrating Standing Waves.** Wilfrid J. Jackson and Frank R. Pratt, *N. J. C. Rutgers University.*—Various devices, such as electrically driven tuning forks and magnetically controlled vibrators, have been used to put into vibration strings under tension and to demonstrate the laws of the vibration of strings discovered by Noble. The apparatus described here is a ruggedly constructed mechanical vibrator. It has some features not found in the similar device described by Pohl. The vibrator consists of a spring-steel strip clamped firmly at one end and resting on a brass eccentric 4.5 cm in diameter with 0.4 cm offset. To help reduce wear the eccentric has shrunk on it a hardened steel sleeve and a fiber tip is fixed to the steel strip at the point of contact. The eccentric together with a counter-weight and pulley are fastened rigidly to a motor-driven shaft which is mounted on ball-bearings. The tension in the cord attached to the steel strip is produced by a spring balance reading up to 2 kg; the balance is mounted in a frame and the tension is changed by means of a screw and crank. The vibrator can be made to operate with three different periods as the pulley on the apparatus and the intermediate pulley on the 1800-r.p.m. motor have the same diameter. The amplitude of vibration may be altered if desired, by changing the position of the steel strip in its clamp. The mountings of the vibrator and spring balance are clamped to the lecture table 200 cm apart or at any other desired distance. With the usual set-up the amplitude of vibration of the loops is about 5 cm wide; so the loops are easily visible over the ordinary lecture room. In the present arrangement the string can be made to vibrate in from 1 to 5 segments. Since the various adjustments can be made easily, the laws of vibrating strings may be tested experimentally before the class.

**8. Tuning Forks for the Measurement of Noise Levels.** L. B. Ham, *University of Arkansas.*—Recently manufactured tuning forks of slow rate of decay are useful in making various energy measurements, such as those of noise levels. They may be used with a fair degree of accuracy in place of the more expensive acoustimeters. Measurements of noise levels in Fayetteville as a regular experiment were made by advanced students using frequencies 128, 256, 512, and 1024 cycles/sec. The noise levels obtained are similar to those of earlier surveys made by means of warbling tone phonograph records and acoustimeters

where the noise was recorded in frequency bands, and where the reference level intensity was taken as $4.4 \times 10^{-16}$ watt. If the new A. S. A. reference level of $10^{-16}$ watt is used, about 7 db must be added to the tuning fork readings. Ordinarily a correction must be added to the energy level at which the calibrated tuning forks are masked by the noise. However, if a group of the frequencies in the noise are in the immediate vicinity of the frequency of the calibrated fork, the masking effect of the noise becomes much greater [Wegel and Lane, Phys. Rev. **23**, 266 (1924)] and, for those frequencies, no correction is needed when the reference level is $4.4 \times 10^{-16}$. Typical noise readings for a Fayetteville residential district on a Saturday afternoon in the order of increasing frequencies of the calibrated tuning forks are: 32, 34, 46 and 26 db. The frequency and energy distribution of traffic noises is essentially the same for all noise levels with the greater portion centering in the vicinity of the 512-cycle fork; thus the decibel energy level given by the 512 fork represents fairly accurately the energy level of the noise, as may be shown by a simple calculation on the noise levels given. These experiments compare favorably with those of E. Z. Stowell [J. O. S. A. **4**, 344 (1933)] who used a compact assembly employing a single frequency of 512 cycles/sec for noise measurements in Newport News.

**9. An Electrostatic Experiment Involving Both Qualitative and Quantitative Measurements.** W. B. Pietenpol, V. P. Lubovich and M. C. Hylan, *University of Colorado.*—Available experiments on electrostatics are too elementary and too general in nature for a college laboratory course. Accordingly, an experiment has been devised which introduces both qualitative and quantitative measurements. Use is made of a modified type of the Shrader electrostatic voltmeter. In its redesigned form it is more sturdy and the suspension is easier to mount or replace. With it the student may (*a*) perform Faraday's ice pail experiment, (*b*) find the relative positions in the electric series of several different substances, (*c*) calibrate the electrostatic voltmeter, (*d*) measure the capacitance of the voltmeter, and (*e*) determine the dielectric constants of several materials. A tall hollow cylinder resting on the top circular plate of the voltmeter serves as the ice pail; charges are introduced by means of a hollow metal sphere suspended on a silk thread. A horizontal metal disk is fastened by an insulating arm to a vertical rod about which as an axis it can be turned. When this disk is swung into position, it and the top plate of the voltmeter form a condenser. The dielectric constants of various materials can be determined by inserting them between the plates. A 600-volt d.c. line is the source of potential; the outlets at the tables are designed to render impossible any danger to the student or apparatus.

**10. An Adaptation of Young's Interference Experiment in the Teaching of General Physics.** W. B. Pietenpol, V. P. Lubovich and M. C. Hylan, *University of Colorado.*—A plate is mounted on one end of an optical bench and illuminated by light made approximately monochromatic by the use of color filters. The plate is divided horizontally, each half having a single vertical slit. These two slits lie in the same plane, one above the other, one fixed and the other movable. On the opposite end of the bench is mounted a plate with two parallel slits so close together as to be indistinguishable except through a microscope. When the single slits in front of the illuminator are viewed through the double slits very fine interference patterns are seen. When the movable and the fixed single slits are in line a single interference pattern is formed. When the movable slit is traversed by means of a micrometer screw its pattern is displaced with respect to that of the fixed slit. If traversed sufficiently the lines of the two patterns will again be aligned. A micrometer microscope is used to determine the distance between the individual slits of the double slit, and the distance the movable single slit has been traversed from the fixed one. From these data, and the distance between the two sets of slits, the student can compute the wave-length of the light.

**11. A Current Balance.** F. W. Warburton, *University of Kentucky.*

**12. A Model of Magnetization.** F. W. Warburton, *University of Kentucky.*

**13. Shadow-Bands Caused by Diffraction.** Richard L. Feldman, *Roosevelt High School, Washington, D. C.*—Shadow bands attending the eclipse of Aug. 31, 1932, were observed at Falls Church, Va., apparently a record for distance from path of totality. A few minutes before maximum darkening, the bands advanced towards the southeast; after maximum, they reappeared, the wave-like form progressing towards the southwest. This points toward a probable circular form, concentric with the shadow and perhaps due to the diffraction which is to be expected past the edge of an opaque body. Any supposition that bands were due to waves in the cirrus formation photographed on the ground, seems improbable because of the unlikelihood of this wave direction changing within a few minutes. Calculation with the diffraction equation seems to substantiate the diffraction hypothesis. So far this hypothesis has been able to explain all reported peculiarities of shadow band appearances, whereas other hypotheses require considerable straining.

**14. An Indicating Lantern Slide Color Mixer.** John J. Heilemann, *University of Pennsylvania.* (By title.)

**15. Experiments on the Saturation Value of the Ion Current Through a Gas. An Interpretation.** F. Palmer, Jr., *Haverford College.*

**16. Flexible Crystal Models.** Isay A. Balinkin, *University of Cincinnati.*

**17. The Composition of Vibrations with Uncorrelated Phases as a Problem in Fluctuations.** G. A. Van Lear, Jr., *University of Oklahoma.*

**18. The Choice and Design of Educational Apparatus for the General Physics Laboratory.** W. L. Kennon, *University of Mississippi.*—The several factors which should determine the choice and design of apparatus intended primarily for laboratory instruction are discussed critically. Specific suggestions are given for designs of apparatus for the study of acceleration due to gravity, projectiles, rota-

tion, the general gas low, conduction of heat, Charles's law, etc.

**19. Some Physics Laboratory Devices.** Newton Gaines. *Texas Christian University.*—(1) A narrow, vertical, wooden channel placed on the free-fall apparatus eliminates danger of accident to students' heads. (2) The Tark safety razor, costing about $1.00, functions perfectly as a 120-cycle vibrator in the Melde experiment; with one vibrator on each laboratory table and a different sized thread used as string on each, a small section can quickly obtain enough data to derive empirically the formula for wave-velocity in a stretched string. (3) The electrified question-and-answer board may be adapted for individual drill in physics.

**20. Some Apparatus for Elementary Laboratories.** Thomas H. Osgood, *University of Toledo.* (By title.)

**21. Lecture Demonstrations as a Staff Project.** Homer L. Dodge, *University of Oklahoma.*

**22. A Physics Course for Students of Music.** R. T. Dufford, *University of Missouri.*

**23. Make Laboratory Experiments More Practical.** C. R. Fountain, *George Peabody College for Teachers.*—To combat the prevailing idea that physics is useful only to those going into engineering, every effort should be made to demonstrate how vital it is to understand the principles that govern the machines in daily use. A typical example is shown where miniature automobile tires are used to study the laws of friction under conditions like those affecting regular tires on various types of roads; calculations are also made to show the relations between the coefficients of friction found and the safe speeds for curves of various radii and for different road and weather conditions. Another illustration is that of a lamp board so wired with switches that 3–4 lamps may be joined in series, in parallel, or in various combinations of series and parallel. The boards are "fool proof" in that it is impossible to make a short circuit by any combination of switches, yet there are 14 different combinations for the board with 3 lamps and 45 with 4 lamps. Students seem to feel, after using these boards, that they have a practical knowledge of circuits. Laboratory instruments are saved by letting the students practice first on the boards.

**24. On the Lack of Logic in the Textbooks and Literature of Physics.** Enos. E. Witmer, *University of Pennsylvania.* (By title.)

**25. Calculus in Physics for Engineers.** W. H. Bennett and H. G. Heil, *Ohio State University.* (By title.)

**26. Direct Low-Precision Experiments.** Edward M. Little; *University of Montana.*—Recently we have drifted toward the direct-type experiments at Montana; elementary laboratory is mainly for mastery of fundamental principles rather than the attainment of technique. Here are eight direct experiments. (1) Newton's second law is illustrated by two unequal weights hung over a light ball-bearing pulley. A metronome beats seconds and the distances fallen from rest are observed. Calculations of average and final velocities, acceleration, kinetic and potential energies, power, impulse and momentum give valuable correlations, being all in one experiment. (2) The corresponding experiment on rotation employs a (siren) disk on a vertical axle. A string wrapped round an enlarged part of the axle passes over a pulley to a falling weight. For the second run two rectangular iron bars are tied on. (3) An irregular block is hung from 2 strings passing over pulleys to weights, and another weight is hung from it off-center. Conditions for equilibrium of forces *not* necessarily meeting in a point are tested. (4) The best example of machines, pedagogically, probably is the screw jack as the calculations of the internal forces, etc. are so involved that the general method must be used. A model screw jack is used. (5) A glass U-tube with arms about 80 cm long is half-filled with mercury. A little water is added to one arm which is then sealed off with the air still in. In a bath, this provides simple apparatus for illustrating $pv=RT$ and vapor pressure. (6) Two magneto magnets are placed so as to produce a zero field as shown by filings. The strength of one is previously determined from its distance from a compass to deflect it 45°. The strength of the other is determined from field vector diagrams. Magnetic potentials are calculated. (7) Using a model transformer of known turns and visible core and a ballistic galvanometer, $L$, $M$, and $\mu$ are calculated all in one experiment, thus giving useful correlations. (8) Cylinder lengths are measured with verniers, diameters with micrometers, and masses with scales. Numerical and percentage maximum and average deviations are calculated for these quantities and also for derived quantities such as area, density, etc. Only data and calculated results are asked for in the reports.

**27. Simple Impromptu Objective Testing.** Edward M. Little, *University of Montana.*—Since it is generally supposed that mimeographing, etc. is necessary in order to give objective tests, many instructors avoid them, especially in small classes where the clerical expense is wasteful. The author employs a simple method that requires no stenographic help, can be used as readily as the recitation-by-turn method, and yet asks everyone in the class *every* question. The instructor prepares a number of multiple choice statements or short problems, gives 3×5-in. slips of paper to the students who make numbered spaces and then reads the first statement to them, repeating if necessary, until it seems they are ready for the next; etc. The students put down the answers (*a* or *b*, etc.) in the appropriate spaces. If this test takes half of the hour the remainder can be used profitably in discussing the correct answers; thus the students do not leave class with wrong ideas. This discussion is *very* live, much more than usual as everyone has labored on each question during the quiz. The students study much more for this kind of recitation; they often take a chance on bluffing their way through the old turn-by-turn recitation. The author prefers double choice statements and simple problems.

**28. Simple Wave Equation Showing Nuclear Boundary or Potential Barrier.** Eric R. Lyon, *Kansas State College.*—The student's approach to the Wentzel-Kramers-Brillouin method in wave mechanics may be simplified by assuming

(1) $\cdots\partial^2u/\partial x^2+(\lambda^2/x^3)(1-\lambda^2/x^2)^{-1}\partial u/\partial x+(4\pi^2/\lambda^2)\times(1-\lambda^2/x^2)^{-1}u=0$. This becomes the wave equation of optics in one dimension, with the time eliminated, when $lim\ \lambda/x=0$: (2) $\cdots\nabla^2u+(4\pi^2/\lambda^2)u=0$. The solutions of Eq. (1) are: (3) $\cdots u=(\lambda/2\pi)\sin 2\,\pi[(x^2-\lambda^2)^{\frac{1}{2}}/\lambda+1/8]\cdots x>\lambda$; and (4) $\cdots u=(\lambda/2\pi)\exp\,[-2\pi(\lambda^2-x^2)^{\frac{1}{2}}/\lambda-0.34657359]$, $x<\lambda$ which join smoothly when $x=\lambda$. If $x$ is measured along a ray, $x=\lambda$ defines uniquely a wave front surface which is the nuclear boundary. In Eq. (3), substitute $h/p=\lambda$, $p^2=2m(E-V)$, $\int p_xdx$ equivalent to $(x^2p^2-h^2)^{\frac{1}{2}}$, $K_1=(h^{\frac{1}{2}}\lambda^{\frac{1}{2}}/2\pi)(2m)^{-\frac{1}{4}}\exp\,(-0.34657359)$, and get (5) $\cdots u=K_1(E-V)^{-\frac{1}{4}}\exp\,(-2\pi i/h)\int p_xdx$. Upon including Eq. (4) in a general W. K. B. solution of Eq. (1), (6) $\cdots u=K_2(E-V)^{-\frac{1}{4}}\exp\,(\pm 2\pi i/h)\int p_xdx$. The intensity is (7) $\cdots u\bar{u}=K_3(E-V)^{-\frac{1}{2}}=K_4/p$. The W. K. B. solution of Eq. (1) shows that the nuclear boundary is a potential barrier. Eq. (1) has a twin: (8) $\cdots\partial^2u/\partial x^2+(\lambda^2/x^3)\times(1-\lambda^2/x^2)^{-1}\partial u/\partial x-(4\pi^2/\lambda^2)(1-\lambda^2/x^2)^{-1}u=0$. The exponential tail of Eq. (1) is inside of the nucleus, and the sinusoid is outside; vice-versa in case of Eq. (8), which affords the basis of a distinction between negative and positive nuclei. The positive nucleus (8) is able to develop harmonics within its interior sinusoidal train, and thus to show an energy and mass in excess of that of the negative nucleus. Certainty of position and uncertainty of momentum may be associated with Eqs. (1) and (8); vice-versa with Eq. (2).

**29. Can College Physics Be Popularized?** EDWIN MORRISON, *Michigan State College.* (By title.)

**30. Content of a First Course in Modern Physics.** JOHN A. ELDRIDGE, *University of Iowa.*—Just as the course in general physics is a survey over a wide field, so the first course in modern physics should be a non-intensive study with broad scope. The field covered should be standardized to a greater extent and the course should give the student easy familiarity with the concepts. The same teaching techniques may be used as in the general course—lecture experiments, simple proofs and many numerical problems.

**31. An Experiment on the Teaching of the Vernier.** C. J. LAPP, *University of Iowa.*—Twenty-five matched pairs of students were selected. One group was taught in the laboratory by the usual method. The other group was taught in the library where they were given special instructions in theory with line-drawing illustrations. A week later both groups were given a functional examination. The students taught in the library were more accurate in reading verniers but took 10 percent longer time to make the reading.

## ANNUAL REPORT OF THE TREASURER

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|---|---|---|
| *Balance brought forward from Dec. 15, 1934* | | $1280.47 |
| CASH RECEIVED | | |
| Dues received[1] | $2137.00 | |
| Donations | 220.90 | |
| 207 paid 5¢ exchange charge | 10.35 | |
| Miscellaneous receipts | 6.80 | |
| *Total Cash Received*[2] | $2375.05 | |
| Total deposited from 12/15/34 to 12/14/35 | | 2375.05 |
| Total Cash Available | | $3655.52 |
| DISBURSEMENTS | | |
| Stationery and supplies | $ 214.03 | |
| Postage | 106.63 | |
| Secretary, Editor's office | 115.50 | |
| Editor's traveling expense | 68.95 | |
| Payments to American Institute of Physics on 1934 account | 1389.05 | |
| Miscellaneous expenses | 5.84 | |
| Service and exchange charges, 11/1/34 to 11/1/35 | 25.96 | |
| | $1925.96 | |
| Total disbursed | | 1925.96 |
| BALANCE ON HAND,[3] Dec. 14, 1935 | | $1729.56 |

PAUL E. KLOPSTEG, *Treasurer*

I have audited the books of account and record of Dr. Paul E. Klopsteg, treasurer of the American Association of Physics Teachers, for the period from Dec. 15, 1934 to Dec. 14, 1935, and hereby certify that the cash as shown by the books of account as having been received has been properly reflected as deposits to the credit of the Association account and that all disbursements have been properly supported by vouchers, and further that the balance on deposit at Dec. 14, 1935, as shown by books of account, has been satisfactorily reconciled with the balance shown by the statement of the Lake View Trust & Savings Bank as of that date.

W. J. LUBY, *C.P.A.*

[1] On Dec. 14 there were 702 members in good standing. Memberships in previous years were: 494 in 1931, 384 in 1932, 437 in 1933 and 694 in 1934.

[2] The American Institute of Physics has credited the accounts of the A. A. P. T. on their books with $226.04, the amount received from the Wood-Beers Committee for the September, 1935 Supplement.

[3] This amount does not indicate the result of 1935 operations, since there is due the American Institute of Physics almost $2000 for the balance on the cost of publication of *The American Physics Teacher* during 1935. The following recapitulation shows approximately the financial picture for 1935; the figures will be known accurately after the audit of the books of the Institute of Physics.

| | | |
|---|---|---|
| Total cost of publication | | $3058.04 |
| Service charge of American Institute of Physics | | 458.71 |
| Expenses already paid by Treasurer for 1935 operations only | | 536.91 |
| | | $4053.66 |
| Income at American Institute of Physics (non-member subscriptions, etc.) | $1320.52 | |
| Income at Treasurer's office (dues, etc.) | 2375.05 | |
| | $3695.57 | |
| Deficit from 1935 operations | | $ 358.09 |

## Available Graduate Appointments and Facilities for Advanced Study in Various Universities and Colleges—1936–1937 (continued)

BEFORE attempting to make use of this information, it is important to consult the foreword to the first part of the list which appeared in the December, 1935 issue, page 194.

**Boston University,** Graduate School, Boston Mass. Apply any time. 2(3) *graduate assistants*, t. remitted; 1(1) *graduate fellow*, $300; 1(1) *graduate fellow*, $150. All appointees assist in lab., etc. Fellows pay part t. *R:* spectroscopy.

**Catholic University of America,** Washington, D. C. 1(1) *graduate assistant*, lab. asst., $800 less $300 f.; 2(2) *K. C. scholars*, room, board and t., less lab. f. For assistantship, apply by letter before May 1 to Prof. George D. Rock; for scholarships, before Mar. 1 to Dean Roy J. Deterrari. *R:* thermionics; spectroscopy; ultrasonics.

**Columbia University,** New York, N. Y. 2(8) *assistants*, lab. teach., $1000 less $20 f.; 4(7) *part-time assistants*, lab. teach. $200–500 less course fees; 2(2) *fellows*, $1000–1500 less $400 t. For assistantships apply by Apr. 1, and for part-time assistantships by July 1, to Prof. George B. Pegram; give qualifications and letter of recommendation with first letter. For fellowships apply on form to University Secretary. *U:* x-rays; magnetism; properties of solids; molecular beams; nuclear physics.

**Dartmouth College,** Hanover, N. H. M only, no form. 0(4) *graduate assistants*, lab. asst., $800. *R:* thermionics; cosmic rays.

**De Pauw University,** Prof. Orrin H. Smith, Greencastle, Ind. Apply any time, M only, no form. 1(1) *graduate assistant*, lab. asst., $200 plus room. *R:* soft x-rays.

**Fordham University,** New York, N. Y. Apply any time, M only, no form. 2(3) *graduate assistants*, lab. asst., $600 less $100–150 t. and f. *R:* geophysics; seismology. *U:* unusually well-equipped seismic observatory.

**Institute of Paper Chemistry** (affiliated with Lawrence College), Dean, Appleton, Wis. May 1. 10–15 *scholars*, service arranged, board, room, remission of t. and f. Besides physics and mathematics, the applicant's undergraduate preparation must include 4 yrs. chemistry, 2 yrs. mechanics, and a ready knowledge of German. *R:* applied optics; mechanics; photoelectricity. *U:* color measurements; optical characteristics of paper; applied photoelectricity.

**Northwestern University,** Evanston, Ill. 1 *fellow* $400; 1 *scholar*, full or half t. remitted; 1 *assistant*, lab. teach., $500 less part t. For assistantships, apply any time by letter to Department; for other appointments apply on form by Mar. 1 to Graduate School. *U:* radiation measurements; electron diffraction; photoelectricity; interferometry and hyperfine structure; infrared spectroscopy.

**Ohio State University,** Columbus, O. 10 (22) *graduate assistants*, lab. asst., grading, $450; 1 (1) *observatory assistant*, making observations at Observatory, $450; 1–2 (1–2) *fellows*, $400; 1 (1) *scholar*, $250. All appointees pay $15 f. For assistantships apply by letter to department chairman; for other appointments apply on form to graduate dean. *R:* nuclear physics; infrared spectroscopy; Zeeman and Paschen-Back effect; band spectra; x-rays and crystal structure; theoretical physics. *U:* infrared spectroscopy; Zeeman effect.

**Purdue University,** Prof. K. Lark-Horovitz, Lafayette, Ind. Apr. 15, no form. 3(10) *half-time assistants*, 9 hr./wk. lab. teach, $700 less library f.; 0(3) *quarter-time assistants*, 6 hr./wk. lab. teach., $350. *R:* x-rays; crystal structure; electron diffraction; spectroscopy; acoustics; nuclear physics. *U:* electron diffraction; crystal structure.

**Smith College,** Northampton, Mass. 1 (1) *teaching fellow*, lab. asst., $600; 1 (1) *graduate fellow*, full-time study, $500. For teaching fellowships apply by letter to Prof. Gladys A. Anslow; for graduate fellowships apply on form to Dean Marjorie Nicolson. *R:* acoustics; electronics; photography; ultraviolet spectroscopy; spectrophotometry.

**Tufts College,** Prof. J. R. Harrison, Medford, Mass. May 1, M only, no form. 0(1) *teaching fellow*, lab. asst., $1000 less $5.00 f. *U:* vacuum tubes; high frequency phenomena.

**University of Arkansas,** Prof. L. B. Ham, Fayetteville, Ark. May 1, M only, no form. 1(2) *graduate assistants*, grading, apparatus, $10–15/mo. less t. and f. *R:* sound and related problems.

**University of Cincinnati,** Graduate School Secretary, Cincinnati, Ohio. Apr. 1. 2(3) *Laws fellows*, $300–500; 1(1) *Hanna fellow*, $500; 1(1) *special fellow*, $250; 3(3) *university scholars*, f. remitted; 12 *graduate scholars*. *R:* mathematical physics; x-ray absorption; soft x-rays; electronics; spectra; photoelasticity; atmospheric electricity.

**University of Iowa,** Prof. G. W. Stewart, Iowa City, Iowa. Several *graduate assistants*, *scholars*, *fellows*, *research assistants* and *research associates*. *R:* spectroscopy; resonance radiation; molecular beams; single crystals; nuclear physics; x-rays, and x-ray diffractions in liquids; electron excitation.

**University of Kentucky,** Prof. Wm. S. Webb, Lexington, Ky. May 15; no form. 4 (5) *graduate assistants*, lab. asst., $500 less $106 t.

**University of Minnesota,** Graduate Dean, Minneapolis, Minn. Apr. 15. 3 (12) *graduate assistants*, lab. asst., $600. *R:* x-rays; electronics; atomic structure. *U:* nuclear physics.

**University of Pittsburgh,** Prof. A. G. Worthing, Pittsburgh, Pa. Apply any time. 4(7) *graduate assistants*, lab. asst., $500.

**University of Utah,** Salt Lake City, Utah. May 1, M only, no form. 2(2) *teaching fellows*, 15 hr./wk. lab. teach., $300 less t. and f. *R:* light; atmospheric electricity; thermionics.

**University of Vermont,** Prof. R. M. Holmes, Burlington, Vt. Apr. 15, M only, no form. 1(1) *graduate assistant*, half-time lab. teach., $800. *R:* photo-conductivity; photo-e.m.f. effects.

**University of Washington,** Seattle, Wash. Mar. 15. 5(12) *teaching fellows*, 15 hr./wk. lab. and class asst., $450–630; 3 *Denny fellows*, open to general univ. competition, $500 max., less $63 t. ($186 for non-residents). For teaching fellowships, apply by letter to Prof. H. L. Brakel; for Denny fellowships apply on form to Graduate Dean.

**Utah State Agricultural College,** Logan, Utah. M only. No regular fellowships available, but part-time employment in related fields may be arranged by communicating at any time with Prof. Willard Gardner. *U:* mechanics of transmission of liquids in soils.

**Vanderbilt University,** Nashville, Tennessee. M. only. 1(1) *graduate scholar*, 6 hr./wk. library, $300 less $175 t. and f.; 2(2) *teaching fellows*, 6–8 hr./wk. lab. asst. etc., $500–$750 less $175 t. and f. For scholarships apply to Graduate Dean; for fellowships, to Prof. F. G. Slack.

**Washington Square College,** Washington Square, New York, N. Y. May 31, no form. 0(3) *graduate assistants*, teach., research, $1000; 0(3) *instructors*, teach., research, $1800. *R:* nuclear physics; spectroscopy (band, infrared, hyperfine, Raman); dielectric constants.

**Wellesley College,** Prof. Louise S. McDowell, Wellesley, Mass. M only, no form. 1(2) *graduate assistants*, 33 hr./wk. lab. asst., grading, etc., $900. *R:* x-rays; dielectrics.

**Wesleyan University,** Middletown, Conn. Apply any time, M only, no form 3(3) *assistants*, lab. asst., grading, etc., $600–800. *U:* piezo-electric resonator investigations.

## Appointment Service: Positions Wanted by A. A. P. T. Members

THE physicists whose announcements appear here are not at present employed in professional capacities. Representatives of departments having vacancies are urged to write to the Editor for additional information concerning those whose announcements interest them. *The existence of a vacancy will not be divulged to anyone without the express permission of the department concerned.*

Any member of the American Association of Physics Teachers who is not employed in a capacity that makes use of his training in physics may register for this appointment service and have a "Position Wanted" announcement published without charge. Departments of physics having vacancies of any kind and industrial concerns needing the services of a physicist are invited to make known their wants through the columns of this journal; there will be no charge for the service. For additional information, address the Editor.

1. Ph.D. Cornell, S.B. Denison. Married. 20 yr. teaching experience, including 5 yr. assoc. prof. state college and 5 yr. head of dept., southeastern univ. Special interest in undergraduate teaching and in building and adapting laboratory apparatus to suit the needs of the student.

2. Ph.D. Indiana; M.S. Kansas State; A.B. Friends Univ. Age 31, married. 2 yr. asst. instr. state univ.; 1 summer, instr. Kansas college. Special fields: conduction of heat and electricity in metals; electrical communication; physical chemistry. Desires position in undergraduate teaching or industrial research.

3. Ph.D. Univ. of Washington; B.S., M.A. Northwestern. Age 45, married, no children. 11 yr. civil engineering work; 15 yr. teaching physics, including 8 yr. college in Orient and 4 yr. head dept. western coed. college. Special fields: magnetism, engineering physics, history of physics. Experienced administrator and executive.

4. Ph.D. Cornell. Age 38, married. 11 yr. teaching in both men's and women's colleges in East and South. Research in electron physics. Special interest in development of demonstration lectures, laboratory experiments and equipment. Glass blowing.

5. Man, 30, married, Ph.D. Yale. 6 yr. teaching experience in eastern universities in most branches of undergraduate physics for both men and women; 3 yr. research associate in radiology in prominent medical school. Supervision of master's theses; research in nuclear physics and thermionics. Broad interests.

6. M.S., N.C. State College; 5 summers grad. work, Univ. of Chicago. Age 39, married. 3 yr. instr. N. C. State College; 5 yr. asst. prof., 7 yr. assoc. prof., Woman's College, University, N. C. Interested in undergraduate teaching or technical research.

7. A.M., A.B. Princeton; 2 yr. additional grad. work in spectroscopy, Princeton and Columbia. Age 30, unmarried. 4 yr. instr. Univ. of Vermont. Special interest in teaching and in developing demonstration and laboratory experiments.

## A Better Financial Outlook for the A. A. P. T.

THE recent action of the executive committee of the American Association of Physics Teachers in providing for *Contributors* and *Sustainers* among the members may help materially to solve the problem of Association finances. It also has the great merit that the dues of members will remain at the present modest figure, so that no one need be excluded from participation in Association activities for financial reasons. The dues will be $3.00 as before, but any member who is able and willing to give additional financial support to the work of the Association and the journal can do so by accepting voluntarily the status of *contributor* or *sustainer*, in which case the amount paid by him will be $7.50 or $15.00 respectively. The executive committee considered various other plans, such as the creation of fellows, but finally decided that any distinctions in the membership involving different dues should be based frankly and solely on the amounts paid voluntarily by the members.

Despite the fact that the report of the treasurer shows a deficit for last year, the general outlook for the Association is highly encouraging. Only a few hundreds of dollars a year additional income are needed to make the Association secure financially and any income beyond this will enable the Association and journal to enlarge their activities. It is generally admitted that the Association and journal during their brief existence have already had a noticeable effect on the status of physics teaching as a profession and on the outlook of physicists engaged in teaching, and it is no exaggeration to say that the possibilities in this direction for the future are large.

Those who have served on the committee on membership have done splendid work in building up the Association rolls, over 300 members having been added through their efforts. Nevertheless, there still remain hundreds of college physics teachers who have, or should have, interests in the teaching aspects of the field but who are not giving the Association support in its work or making it possible for the Association to be useful to them. Unquestionably some of these teachers, despite the fact that they teach physics in colleges, are not trained or interested primarily in physics and do not consider themselves members of the profession of physics. With this relatively small group we are not concerned here. But there is a growing sentiment that those teachers who legitimately may be regarded as physicists should consider connection with the Association a professional obligation. If this sentiment is fostered and the new plan of providing definitely for contributors and sustainers proves successful, the faith thus expressed by the membership will be justified without much doubt by the contributions of the Association both to physics teaching and to the profession of physics as a whole.—D. R.

# DIGEST OF PERIODICAL LITERATURE

## Laboratory and Demonstration Practice

**Rubber stoppers.** N. W. Matthews; *Chem. Analyst* **24**, 20, July, 1935. To remove a rubber stopper that has become cemented to glass or metal tubing, pour a little 95-percent alcohol around the tubing at the stopper and allow it to soak a few minutes.

**An improved stopcock grease.** L. C. Case; *Chem. Analyst* **24**, 18, July, 1935. To improve ordinary stopcock grease, melt it and stir in a little finely powdered graphite. This gives better lubrication and longer service, and prevents the freezing of stopcocks.

**An efficient, inexpensive hot plate.** L. C. Kreider: *J. Chem. Ed.* **12**, 336–7, July, 1935. A hot plate which furnishes a safe, convenient and cheap source of heat at temperatures of 30–70°C can be built from readily available materials at a cost of about 50 cts. A porcelain light socket containing a 100-watt lamp is mounted on a wooden block $15\times15\times2$ cm. The top is removed from a tin can about 10 cm in diameter and 12 cm high, and a hole 4 cm in diameter is cut in the bottom. Three heavy tin strips, $2\times9$ cm, are soldered to the sides of the can near the base to form a tripod that will hold the can rigidly over the light socket and 6 cm above the wooden base. Heavy wire gauze, 2 cm larger in diameter than the can, has radial slits cut to a depth of 1 cm from the outside edge at short intervals around the circumference. The flaps thus formed are then bent at right angles to fit snugly over the outside of the open top of the can. The outside of the can is insulated with asbestos paper bound with copper wire. The lower temperatures are obtained by placing the vessel to be heated on a ringstand at some height above the wire gauze.

## Physics Teaching and Science Education

**The contribution of laboratory work to general education.** H. I. Schlesinger; *J. Chem. Ed.* **12**, 524–28, Nov., 1935. Laboratory work for students is under fire, for it is being urged that individual experiments be replaced by such methods as lecture demonstrations. Many administrators doubtless favor this view simply because it will effect economies, but others support it with the belief that nothing will be lost by the change or even claim for it distinct educational advantages. In truth there is a widespread dissatisfaction among teachers with the results of laboratory instruction. Students, on the other hand, usually look forward to such work with pleasure; in the General Course at Chicago they often complain that there are no individual experiments other than the little provided, as a substitute, by the self-operative demonstrations in the physics museum. Too frequently, however, their enthusiasm wanes when laboratory work actually is encountered, and their real interest degenerates into mechanical performance of experiments to get results expected, rather than to observe what actually is going on.

Another major objection to the student laboratory has arisen from the present marked trend to make the last two years of secondary school and the first two years of college a period of "general education." Many supporters of this movement believe that laboratory work is essentially technical and hence should be eliminated from these years except for students who plan to enter a science or, at least, who have shown special aptitude. Their argument involves the two assumptions that courses intended for general education differ in objective from those for the prospective professional student, and that laboratory work has value only as a part of technical training.

A rather careful study of objectives reveals that, in chemistry at least, most teachers are guided by the following aims in planning elementary laboratory courses: (1) to illustrate and clarify principles discussed in the classroom, by providing actual contact with materials; (2) to give the student a feeling of the reality of science by an encounter with phenomena which otherwise might be to him no more than words; (3) to make the facts of science easy enough to learn and impressive enough to remember; (4) to give the student some insight into basic laboratory methods, to let him use and to train his hands. A questionary recently sent out from Syracuse University also substantiates the belief that the objectives just stated really are the motivating ones in the minds of most chemistry teachers.

The main cause of the present controversy over the laboratory lies in making these aims the chief ones of laboratory teaching. Without question they are important and no laboratory course can afford to neglect them. But many believe that they can be achieved just as effectively by lecture or small-group demonstrations, or at least effectively enough so far as the non-science major is concerned. To settle the question many attempts are being made by teachers and psychologists to measure the relative effectiveness of the two methods but all these studies appear to have more or less implicitly assumed the validity of the four aims mentioned. Granting the importance of these aims, they nevertheless may not be the fundamental ones, in which case such studies cannot lead to valuable conclusions. A re-examination of the function of individual laboratory work thus becomes necessary. In doing this it is best to consider first the function of laboratory work as a part of general education; later it will be seen that this limitation will not result in a neglect of the needs of the science major.

General education is defined in many ways but usually is assumed to include a certain minimum of factual information, at least an acquaintance with the great

principles of the natural and social sciences, and an appreciation of trends in philosophy and in art. Though opinion may differ on the relative importance or even inclusion of some of these items, everyone agrees that a main purpose of a general education is to train students in clear thinking. Some thought will show, however, that there are two other objectives of equal significance. One is to teach students how and what to see; in most problems confronting mankind, ratiocination must be preceded by accurate observation and a wise choice of premises, and must be checked by further observation. To learn to do this correctly and objectively requires guidance just as does learning how to think. The second significant objective grows out of the fact that most students are not preparing for the contemplative life of the scholar but for careers crowded with activity; and the guidance of this strong impulse has been left by education almost entirely to opportunities created by the student himself in connection with the much-scorned student activities. Any educational scheme is seriously defective if it does not include planned training in the art of translating observation and thought into well-considered action.

In this synthesis of observation, reflection, and action into a pattern of behavior, physical science laboratory work is one of the most powerful tools. It gives ample scope for the development of the ability to observe. Unlike biology, it can be rendered simple enough to make analysis possible for the beginner. It can be made to demand of the student that he check his conclusions by further experiment of his own design. Training thus is provided in observation, in thought and in considered action. Indeed we now see that these objectives are not fundamentally new but that doubtless they guided pioneer scientists in training their small groups in the famous old laboratories. But with the increase in the number of students, in their interests and in the contents of the sciences, these larger purposes were lost to sight. Certainly if they were again made the chief aims of laboratory instruction, it never would be supposed that demonstrations can be anything more than a poor substitute for individual laboratory exercises. Watching demonstrations gives little opportunity to observe anything but what is pointed out to one, and none to carry into practice any procedure suggested by one's thinking.

In trying to recapture the spirit which should dominate a class working toward such objectives, we should first examine present experiments to see if any of them are to be excluded because they merely illustrate subject matter, or merely give opportunities to ask leading questions. Next, experiments should be provided whose results the student cannot readily predetermine by reference to the textbook; these will help develop the ability to observe. Of course the beginner must start with exercises that demand little more than following suggestions, so that he may acquire that minimum of technic without which nothing can be accomplished and may learn to record his work accurately and independently. But even this introductory part can be improved in the light of our objectives, probably by concentrating attention on methods of observation and frankly neglecting other considerations. The experiments which follow the introductory ones and which really are to accomplish our major purpose, are very difficult to plan. At Chicago only a beginning has been made with them and nothing done so far is considered as final.

Sometimes a small change in the directions for a traditional exercise is enough; thus "Prove that aluminum hydroxide is a weak base" is better than "Test an aqueous solution of aluminum hydroxide with litmus paper." More frequently a slight modification of the experiment itself accomplishes much. Instead of having the student determine the density of copper, ask him to conclude from the result of his density determination which one of a limited selection of metals has been given to him; and then, since density does not define a metal uniquely, have him look up other properties of the substance and corroborate his conclusion by tests suggested by himself. This provides connected exercises and incentives.

Another type of experiment is that in which the results may vary greatly with repeated trials; this promotes interest and discussion and leads to finding the causes of the differences observed. Other experiments may be based on the various stock classroom arguments that always arise every year. If the students ask in the class the simplest way to carry out a certain procedure, rather than give an answer, encourage them to show some initiative in developing methods of their own. Have them devise apparatus for the suggested methods and thus learn from experience the criteria of simple and convenient procedures. The important point is to require the student to put his suggestion into practice if it is at all feasible, or even to have him try, without penalty, an inadequate method, provided he can thereby discover for himself the reason for his failure.

One is struck with the average student's indifference to what we consider the esthetic side of laboratory phenomena. Perhaps this is because he lacks our experience with experiments that fail, and hence sees nothing unusual in one that succeeds. Whereas teachers have striven to devise many striking and beautiful lecture demonstrations, they have not made the same effort in planning the student's own work. Efforts in this direction should be repaid amply by the results.

With the recognition that illustration of phenomena and development of skills, though important, are not the sole objectives, the number of experiments can be decreased to give students more time to observe, to think and to develop initiative. The value of so-called quantitative chemistry experiments needs to be studied in terms of our broader objectives. If the laboratory ceases to be primarily a means of illustrating subject matter, the laboratory and classroom need not necessarily keep in step. One might begin with intensive classroom work, gradually introduce the first experiments on primary technics and finally reach a stage of intensive laboratory work with but few lectures. Something like this has been done in some secondary schools, but is yet to be shown to be feasible for colleges.

The original paper should be consulted for other details, especially on various chemical experiments suitable for achieving the objectives emphasized.

# THE AMERICAN INSTITUTE OF PHYSICS

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The American Institute of Physics is a membership corporation of which five societies are the founding members. These five societies are the principal national societies devoted to pure and applied physics in America. Their names, and those of their representatives who form the Governing Board of the Institute, are given above. The principal work of the Institute is the publication of journals sponsored by the societies or by itself. The names and the editors of the journals are also listed above.

The broad purpose of the Institute is to represent, in all matters of wide or common interest, the five thousand or more members and subscribers associated with the Founder Societies and the journals. It aims to advance the science and profession of physics, and to promote cooperation between pure research, the applied sciences and the industries. To achieve these aims, it is greatly in need of an endowment and is empowered by law to administer grants and funds of any kind.

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